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SPACE SYSTEMS

THERMIONIC SPACECRAFT DESIGN STUDY

FINAL REPORT

JUNE 30, 1970

PREPARED UNDER CONTRACT JPL 952381
FOR
THERMIONIC REACTOR SYSTEMS PROJECT

PROPULSION RESEARCH AND ADVANCED CONCEPTS SECTION
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GENERAL ELECTRIC

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NSP NUCLEAR SYSTEMS PROGRAMS

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NUCLEAR SYSTEMS PROGRAMS
GENERAL ELECTRIC
SPACE DIVISION

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TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

TABLE OF CONTENTS (Cont'd)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

ABSTRACT

This report presents the results of a design study of nuclear-electric propelled unmanned spacecraft. The electric power source is in-core thermionic reactors based on either the internally (flashlight) or externally fueled diode concept. The study guidelines and approach are defined. The characteristics of the candidate launch vehicles, thrust subsystem, and the payload and communications subsystem are presented.

The definition of two spacecraft/powerplant configurations are presented which deliver 240 kWe net to the thruster array. This definition, presented for both the flashlight and externally fueled reactors includes the key items of spacecraft arrangement and a detailed weight breakdown. Power conditioning, heat rejection subsystem, shielding, and spacecraft structure are detailed. The results show about a 30 percent weight advantage for the spacecraft based on the externally fueled reactor. This is primarily due to a 120 vdc power output from the externally fueled reactor, as compared to a 15 vdc power output from the flashlight reactor.

Weight reduction by improved technology could further reduce the weight by 5 to 15 percent.

1. SUMMARY

1. SUMMARY

Preliminary design analysis to determine spacecraft component arrangement and configuration was conducted. The resultant spacecraft design referred to as the baseline concept, with guidance from the weight optimization computer code studies, has resulted in a refined design layout.

Reference spacecraft design layouts, and weight and power distribution summaries are presented for each of the two powerplant concepts. For this study, the externally fueled reactor and flashlight reactor concepts are required to provide 240 kWe to the thrust system. Comparison of the two powerplant concepts and their effect on the total spacecraft are presented below. Each of the reference designs were developed under the common guidelines that all of the powerplant components, except the reactor, are current technology.

1.1 PERFORMANCE COMPARISON

Using terminology recommended by the NASA-OART electric propulsion systems analysis task group (Reference 1), the spacecraft initial mass, m_o, is defined as:

$$m_o = m_{ps} + m_p + m_t + m_n$$

where the masses are

m_{ps} = low thrust propulsion system

m_p = propellant

m_t = tankage

m_n = net spacecraft (guidance, thermal control, attitude control, telecommunications, structure, science, etc.) - includes the science payload, m_L

The propulsion system is further broken down:

$$m_{ps} = m_w + m_{ts}$$

where these masses are

m_w = power subsystem

m_{ts} = thrust subsystem

Similarly, net propulsion power is defined as

$$P_{NP} = P_{TN} + P_{TPC}$$

where the component powers are

P_{TN} = ion engine grid power

P_{TPC} = other ion engine power

Gross reactor power is that reactor output power required to supply net propulsion power, P_{NP}, to the thruster subsystem. Gross propulsion power is given by:

$$P_e = P_{NP}/\eta_{MPC}$$

where η_{MPC} is the main power conditioning efficiency. Specific weight of the propulsion system, α, is defined by

$$\alpha = \frac{m_{ps}}{P_e}$$

From the detailed weight and power breakdown, presented in Tables 1-2 and 1-3 for the externally fueled reactor and in Tables 1-4 and 1-5 for the flashlight reactor, spacecraft performance is summarized in Table 1-1 for the state-of-art spacecraft designs. Also shown are performance data credible for advanced spacecraft concepts (Section 8) which account for the weight reduction associated with the following:

a. Replacement of Cu/SS radiators by Be/SS radiators for the 0.95 non-puncture probability.

TABLE 1-1. SPACECRAFT PERFORMANCE COMPARISON - REFERENCE BASELINE DESIGN AND ADVANCED CONCEPTS

Reactor	Externally Fueled Reactor Spacecraft		Flashlight Reactor Spacecraft	
	State of Art*	Advanced	State of Art*	Advanced
M_{eo} - pounds Lift-off mass	31280 (14200)**	29015 (13200)	37605 (17100)	34970
M_o - pounds Initial mass	30190 (13700)	27940 (12700)	36325 (16500)	33690
M_{ps} - pounds Low thrust propulsion system	13210 (6000)	10960 (4980)	19330 (8790)	16710
M_w - pounds Power subsystem	9045 (4106)	8235 (3790)	12170 (5525)	10950
M_{ts} - pounds Thrust subsystem	4165 (1891)	2725 (1250)	7160 (3250)	5760
M_p - pounds Propellant	14500 (6580)	14500 (6580)	14500 (6580)	14500 (6580)
M_t - pounds Tankage	245 (111)	245 (111)	245 (111)	245 (111)
M_n - pounds Net spacecraft	2235 (1015)	2235 (1015)	2235 (1015)	2235 (1015)
M_e - pounds Science payload	2065 (~1000)	2065 (~1000)	2065 (~1000)	2065 (~1000)
P_G - kWe Reactor gross power	274	274	318	318
P_e ~ kWe Effective power input to PC units	262	262	274	274
P_{NP} ~ kWe Net propulsion power	240	240	240	240
P_{TH} ~ kWe Ion engine grid power	223	223	223	223
P_{TPC} ~ kWe Other ion engine power	17	17	17	17
α ~ pounds/kWe*** Special weight	50.4	41.8	71.1	61.0

*Except for Reactor
**Numbers in parenthesis are weights in kilograms
***Based upon M_{ps}/P_e

b. Increasing the maximum power conditioning temperature from 200°F to 300°F.

c. Increasing the main power conditioning efficiency by 2 percent.

d. Decreasing the critical power conditioning temperature drop from the transistor junction to the radiator surface from 25°F to 15°F.

Structure weight is assumed to decrease in direct proportion to the decrease in the total low thrust propulsion system weight, M_{ps}.

Propulsion system specific weight, α, for the reference externally fueled reactor/spacecraft is 50.4 pounds/kWe, and propulsion system specific weight of the reference flashlight reactor/spacecraft is 71.1 pounds/kWe. These specific weights are based on propulsion system power input of 262 kWe for the externally fueled reactor/spacecraft and 273.1 kWe for the flashlight reactor/spacecraft. Table 1-1 indicates that technology advancements in the spacecraft, external to the reactor, can result in performance increases of about 12 percent for both systems.

1.2 EXTERNALLY FUELED REACTOR BASED SPACECRAFT

The reference spacecraft utilizing the externally fueled reactor concept is based on the following assumptions:

a. Reactor coolant outlet temperature of 1350°F.

b. Single heat rejection loop between reactor and main radiator.

c. Main radiator in a position directly behind the forward Hg propellant tank and in front of the power conditioning radiator.

Further details are presented in Subsection 7.1.

1.2.1 REFERENCE DESIGN LAYOUT

Figure 1-1 shows a design layout of the spacecraft powered by the externally fueled reactor. The reference spacecraft is approximately 62.7 feet long and 9.2 feet in diameter. The conically shaped forward end of the spacecraft includes the reactor at the apex and 75 percent of the main radiator. Half-angle of the conical portion if 6.6 degrees. The remainder of the vehicle from this point rearward is essentially a cylinder.

Figure 1-1 provides an overall arrangement of the major spacecraft components. The reactor is located at the apex of the conical section to provide maximum separation distance from the payload at the opposite end of the spacecraft and to assure minimum required shield volume. The shield consists of a LiH block of neutron shielding followed by the forward tank of mercury (Hg) propellant which acts as a gamma shield.

Located directly behind the propellant tank is the main radiator, which dissipates waste heat from the reactor by means of a single loop NaK-78 coolant. A very short section of auxiliary radiator, which dissipates heat generated in the EM pumps and the neutron shield, separates the main radiator from the power conditioning radiator. Individual power conditioning modules are placed uniformly on the eight-sided power conditioning radiator. Low voltage cables extend longitudinally from the reactor exit along the surfaces of the shield and main radiator to the power conditioning radiator. At five axial locations on the radiator, these cables run circumferentially to the 38 individual modules. Thirty-seven of these modules are required for the 37 ion engines, of which 31 are operational and 6 are spares. The remaining PC module provides for the necessary hotel load power conditioning.

The rear section of the spacecraft includes the Hg propellant not required for gamma shielding, the payload bay, and the thrust bay that houses 37 mercury ion engines. A communication antenna which extends radially for operation is shown in the stowed position behind the thrusters for launch.

Cross-sectional views through the main radiator, power conditioning radiator, and payload sections of the externally fueled reactor/spacecraft are presented in Figures 1-2, 1-3, and 1-4, respectively.

1.2.2 WEIGHT AND POWER SUMMARY

The weight summary for the reference designs of the spacecraft utilizing the externally fueled reactor concept is presented in Table 1-2. In order to provide 240 kWe of power to the ion engine system, a gross reactor power output of 274 kWe is required. Total spacecraft weight at launch is 31,485 pounds. Disposable launch vehicle adapter and payload shroud weights, which are jettisoned, result in an Earth orbit spacecraft weight of 30,410 pounds.

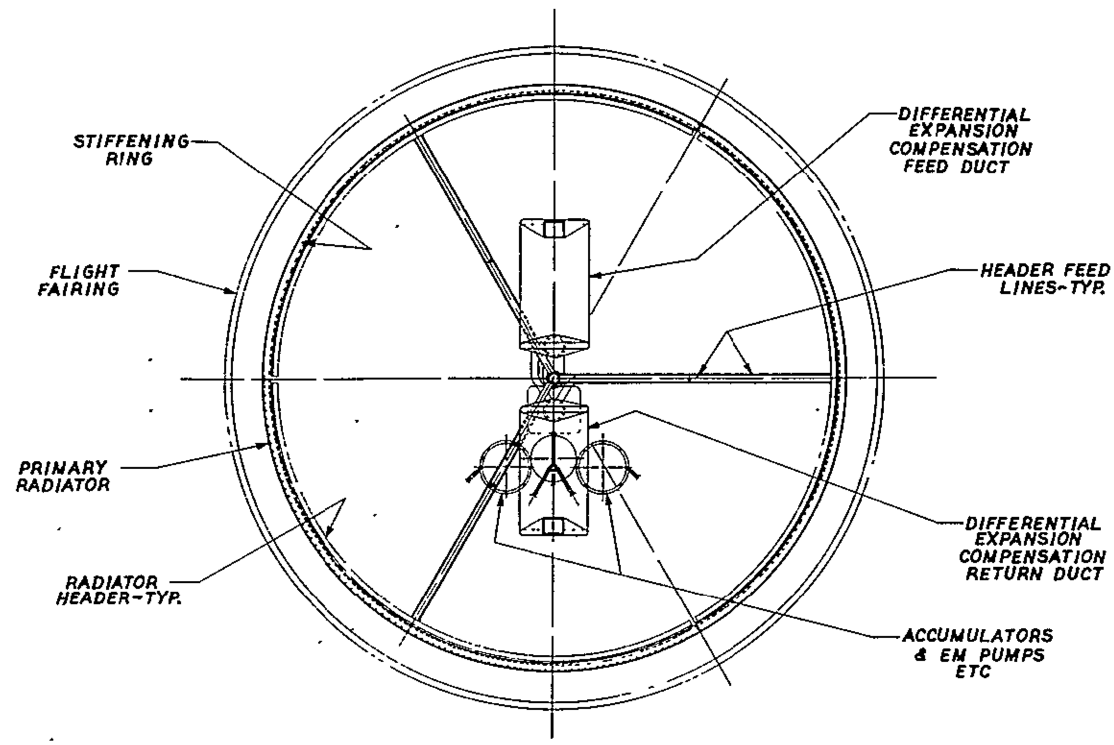

Figure 1-2. Main Radiator Cross-Sectional View, Externally Fueled Reactor/Spacecraft

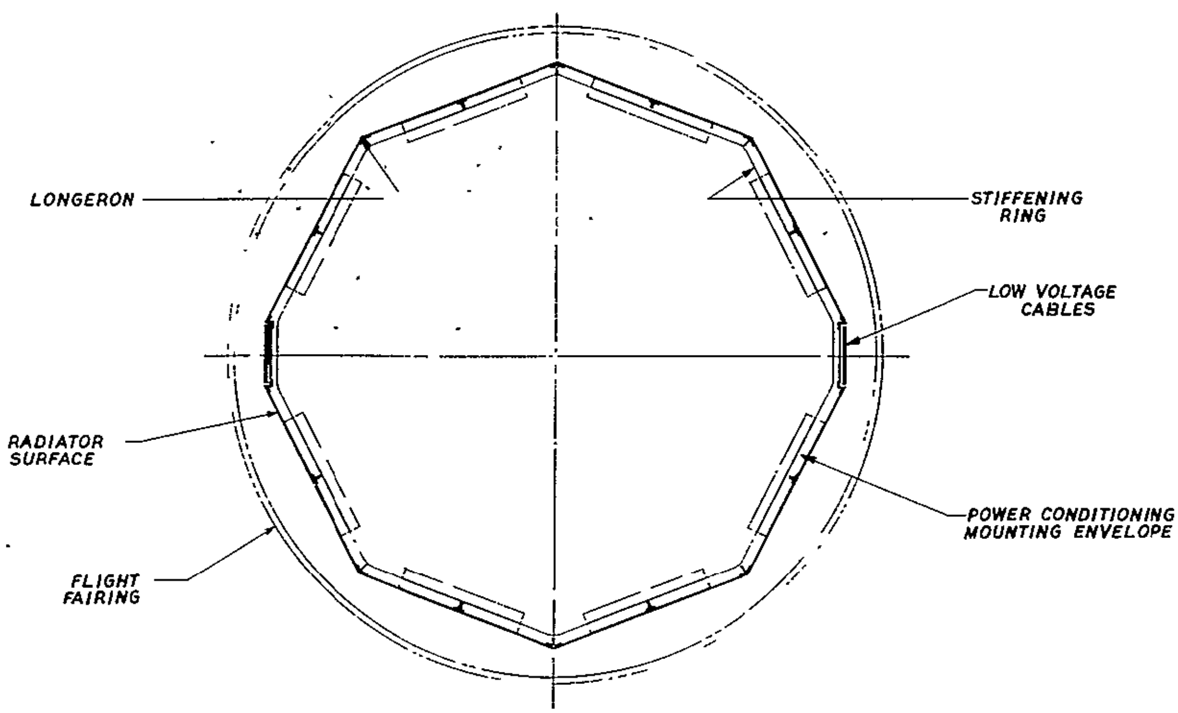

Figure 1-3. Power Conditioning Radiator Cross-Sectional View, Externally Fueled Reactor/Spacecraft

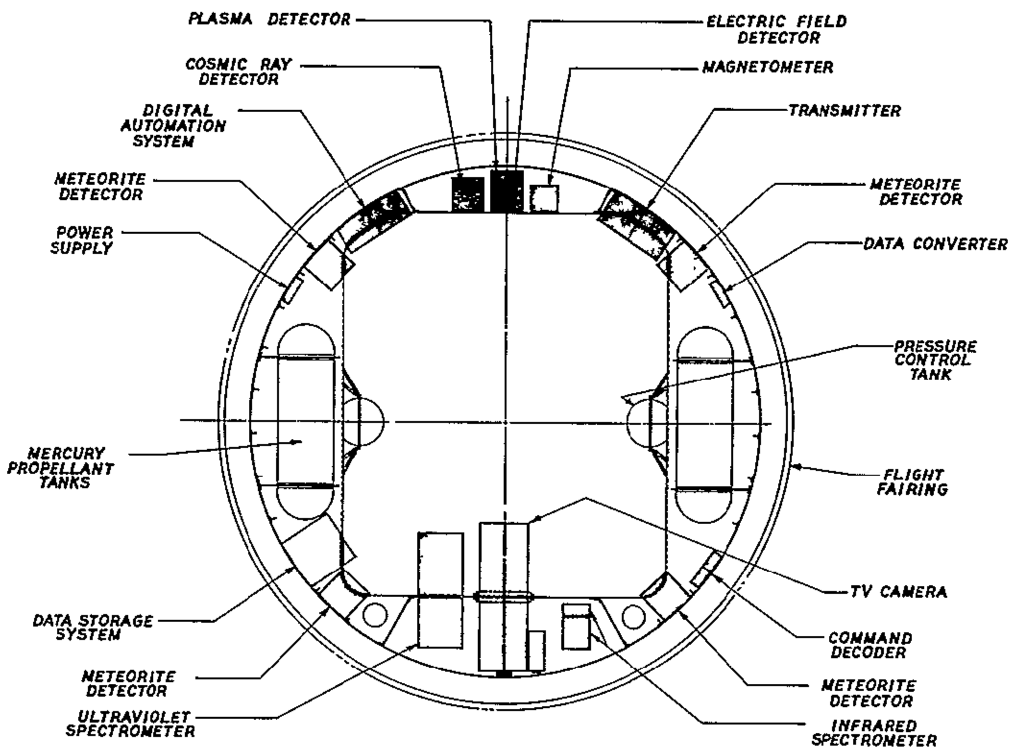

Figure 1-4. Payload Bay Cross-Sectional View, Externally Fueled Reactor/Spacecraft

Weight of each of the three major spacecraft systems are:

a.	Propulsion system	13,210 pounds
b.	Propellant	14,500 pounds
c.	Propellant inert	260 pounds
d.	Payload system	2,235 pounds

Electric power utilization for the externally fueled reactor concept is summarized in Table 1-3. Net power to the ion engine system is 240 kWe, of which 223 kWe are required for the 3100 volt screen supply operation of the ion engines, and 17 kWe are required for other special ion engine power conditioning. A total of 274 kWe of gross reactor output power is required.

TABLE 1-3. ELECTRIC POWER SUMMARY 240 kWe (NET) THERMIONIC SPACECRAFT (EXTERNALLY FUELED REACTOR)

Component	Power	kWe	
Reactor Output			274
Low Voltage cable loss		5.87	
Hotel load section		4.031	
Cable losses	.055		
PC losses	.5246		
Reactor pump input	2.745		
Auxiliary pump input	.0064		
Reactor controls input	.20		
Cesium heater input	.50		
Payload and Thrust section		19.1	
Cable losses	0.1		
Special Ion Engine PC input	17.0		
Payload input	1.0		
Spacecraft control input	0.5		
Powerplant control	0.5		
High Voltage PC Input		245	
PC losses	21.5		
Cable losses	0.5		
Thruster Engine Input	223		
Net Power to Thruster*			240

*The net power is the sum of the ion engine grid power input, after power conditioning, and the other special ion engine power.

For purposes of mission analyses, 262 kWe are delivered to the main power conditioning, which operates at an effective efficiency of 91.6 percent, including high voltage cable losses, to deliver 240 kWe to the 31 operating ion engines.

1.2.3 KEY CHARACTERISTICS

A summary of design characteristics of the shield, heat rejection and power conditioning subsystems are discussed in this section for the externally fueled reactor spacecraft reference design.

1.2.3.1 Reactor-Shield Subsystem

Shielding is provided to ensure that the power conditioning and payload components meet the radiation criteria established by the design guidelines. Neutron radiation is attenuated by a lithium hydride shield, located immediately behind the externally fueled reactor.

Additional attenuation is provided by the tank of mercury propellant located behind the shield. However, the primary purpose of mercury propellant in the forward section is to act as the primary gamma shield.

The lithium hydride shield is 16 inches thick with an average diameter of 41.8 inches. Total weight of the neutron shield is 765 pounds, of which 575 pounds is lithium hydride.

Approximately 4500 pounds of mercury propellant is contained in the tank located directly behind the shield. The conically shaped tank is 6 inches thick with an average diameter of 44.4 inches.

Plugs of tungsten weighing 185 pounds back up the propellant shield where auxiliary coolant lines pass through the propellant tank.

1.2.3.2 Heat Rejection Subsystem

Heat rejection from the spacecraft is accomplished by the primary, auxiliary, power conditioning, payload and thruster PC radiators. The primary and auxiliary radiators are part of an active cooling network; whereas, the power conditioning, payload and thruster radiators transfer heat from temperature sensitive components to space by passive means. In both the primary and auxiliary active loops, NaK-78 is used as the coolant fluid. The payload and thrust subsystem have essentially been defined by the design guidelines.

The function of the primary heat rejection system is to actively transfer heat from the reactor to space. The main radiator is located in the forward section of the spacecraft because the high reactor output voltage, about 120 volts, permits the aft location of the power conditioning radiator without excessive I^2R losses. The forward location of the main radiator also minimizes coolant and piping weight, and the weight penalty associated with NaK-78 coolant pumping.

The relative location of the main heat rejection system is shown in Figure 1-1. The main radiator consists of four bays of equal length, three of which form the conical surface of the spacecraft while the fourth occupies the forward section of the cylindrical spacecraft area. Each of the bays is divided into three 120° panels. Dry weight of the copper/stainless steel radiator, which is 660 square feet in area, and associated headers is 1335 pounds. In addition to the required piping and two EM pumps (one working and one redundant), bellows in the input and return radiator feed lines takes up extension motion among the individual bays of the main radiator.

1.2.3.3 Power Conditioning

Low voltage cables transports 120 volts of reactor electrical power output to the 37 high voltage supply power conditioning units, the special payload and thrust power conditioning modules and hotel load low voltage power module. Path of the low voltage cables is shown in Figure 1-1. Each of the 37 main power conditioning modules supplies 3100 volts to each ion engine. The hotel power conditioning distributes low voltage power to operate the power plant as well as the electronic components which monitor and control the actuator drives of the reactor and the pumps of the active heat rejection loops in the power plant.

Located directly behind the auxiliary radiator is the passive power conditioning radiator, also shown on Figure 1-1. The 38 power conditioning modules are placed uniformly over the aluminum radiator in which 480 square feet are required to dissipate waste heat to space. This radiator, based on a 0.115 inch panel thickness, weighs 745 pounds.

1.3 FLASHLIGHT REACTOR/SPACECRAFT

The reference flashlight power plant and spacecraft design is based on the following requirements:

a. Reactor coolant outlet temperature of $1350^{\circ}F$

b. Two heat rejection loops in series between reactor and main radiator

c. Power conditioning radiator located directly behind the shield and in front of the main radiator

d. Aluminum as the low voltage cable material.

1.3.1 REFERENCE DESIGN LAYOUT-FLASHLIGHT REACTOR SPACECRAFT

Figure 1-5 presents the design layout of the spacecraft powered by the flashlight reactor. The reference design spacecraft is a long, narrow vehicle, approximately 84 feet long and 9.2 feet in diameter. The conical front end section is 25.6 feet long with a 7.4 degree half angle while the rear of the vehicle is essentially a cylindrical section. The reactor is located at the apex of the conical section to provide maximum separation distance from the payload, which is at the rear of the cylindrical section, and to assure minimum required shadow shield volume. The neutron shield is located as close as possible to the reactor, again to provide minimum shield volume and weight, with a portion of the mercury propellant located in a tank behind the neutron shield to act as gamma shielding.

The power conditioning modules and power conditioning radiator section are located directly behind the shield and propellant tank to minimize the length and, hence, the power losses in the low voltage cable. This is required due to the low voltage, 14 to 16 volts, characteristic of the flashlight reactor. Individual PC modules are distributed uniformly on the surface of the PC radiator, one module per pair of reactor fuel elements and low voltage cables. The cables are strung along the outer surface of the shield and PC radiator surface so that they can radiate their I^2R power losses directly to space.

The PC radiator occupies most the conical surface of the spacecraft plus 9.7 feet of the cylindrical section. A very short section auxiliary radiator surface, together with internal insulation rings, acts as a thermal buffer between the low temperature PC radiator and the high temperature main radiator, which covers most of the cylindrical section surface.

The reactor waste heat is transported to the main radiator in two stages. The first loop pipes the NaK-78 reactor coolant, outside the shield to a heat exchanger placed between the neutron shield and the gamma shield (forward propellant tank). A second NaK-78 loop carries the heat along the outer surface of the PC radiator to the main radiator. The nominal $1300^{\circ}F$ duct is insulated from the $175^{\circ}F$ power conditioning radiator by combined nickel/aluminum multifoil insulation.

Two series coolant loops are required because of unacceptable coolant activation due to the beryllium or beryllium oxide reflectors used in the flashlight reactor. This differs from the externally fueled reactor because of its heavy metal reflectors, which reduce coolant activation to the point where a single loop is acceptable. Comparing Tables 1-2 and 1-4, it is seen that the externally fueled reactor weighs about 1,000 pounds more than the flashlight reactor. This is more than offset by a 2,300 pound reduction in the primary heat rejection system for the externally fueled reactor, relative to the flashlight reactor.

The payload section, thrust power conditioning section, and ion thruster engines are located in sequence at the rear of the vehicle. A single disk communication antenna is shown in the launch position behind the thruster engines on Figure 1-5. After launch, it would be extended radially, beyond the vehicle diameter and forward of the thrust engines.

Cross-sectional views through the heat exchanger bay, power conditioning radiator, main radiator, and payload sections of the flashlight reactor/spacecraft are presented in Figure 1-6, 1-7, 1-8, and 1-9, respectively.

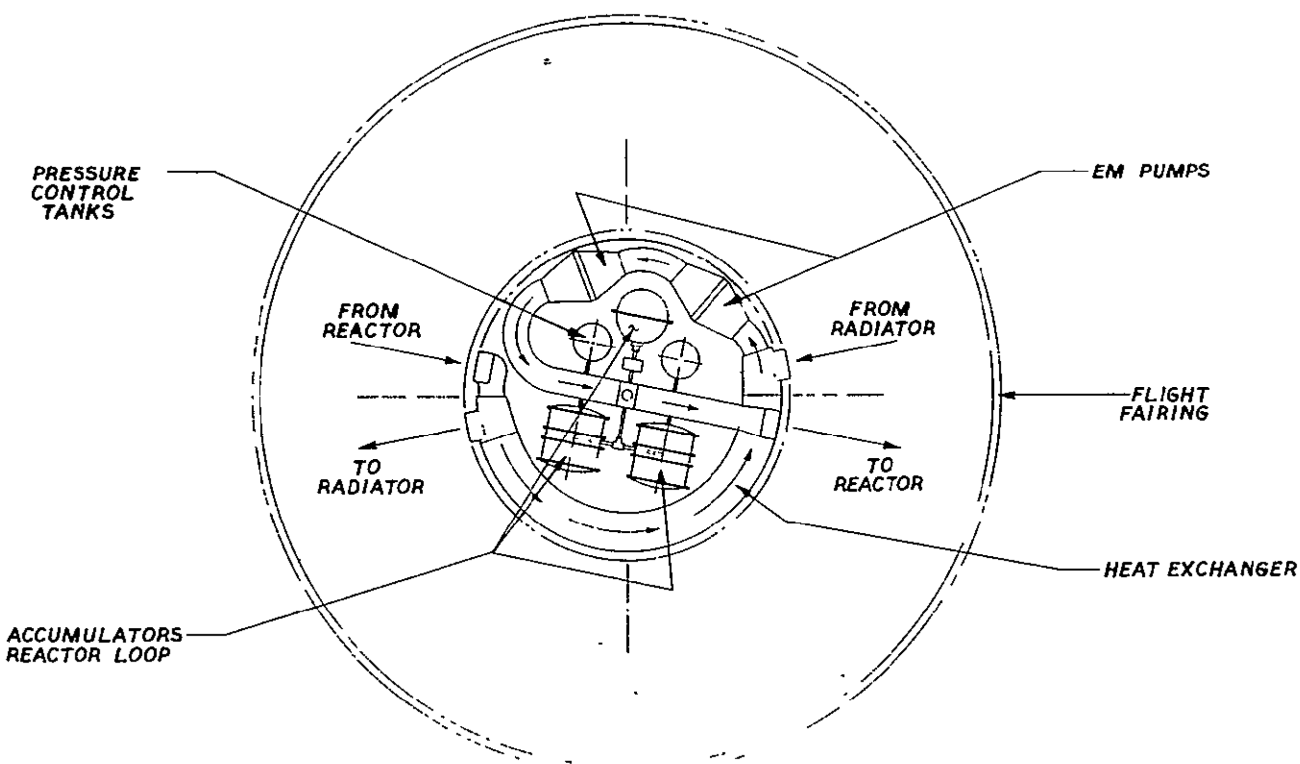

Figure 1-6. Equipment Bay Cross-Sectional View, Flashlight Reactor/Spacecraft

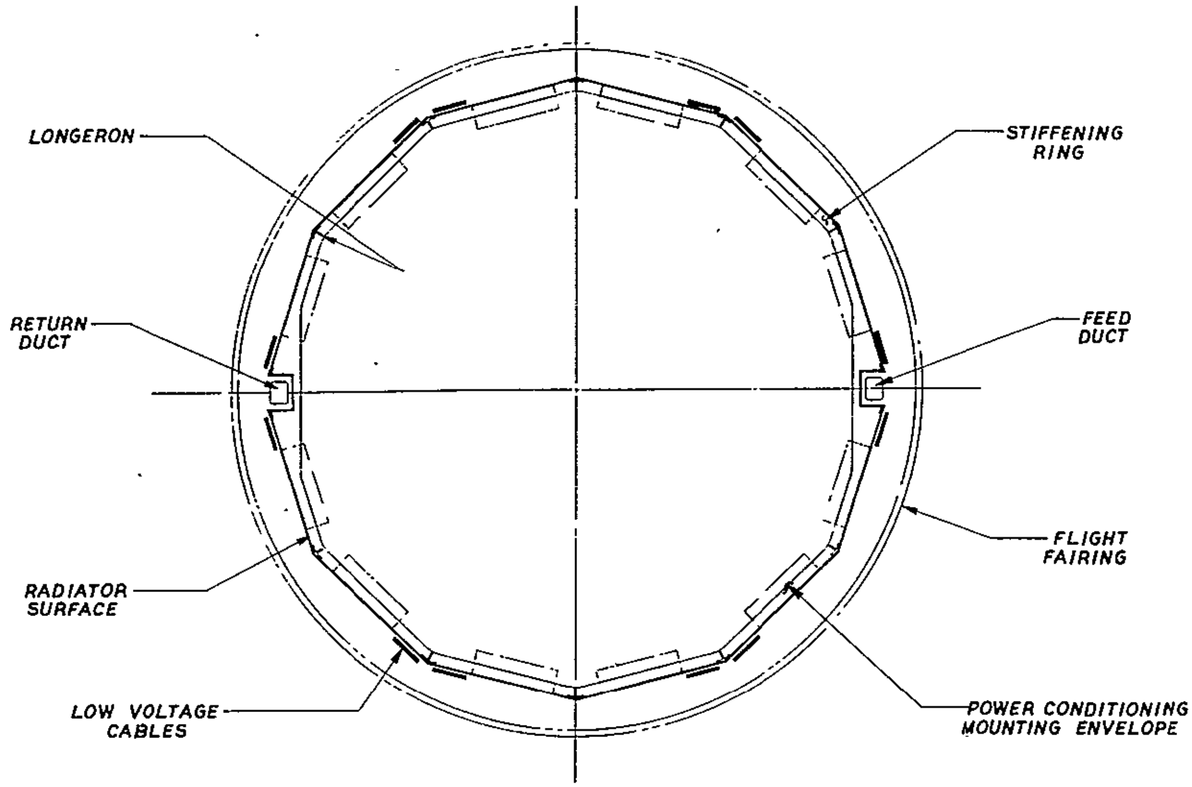

Figure 1-7. Power Conditioning Radiator Cross-Sectional View, Flashlight Reactor/Spacecraft

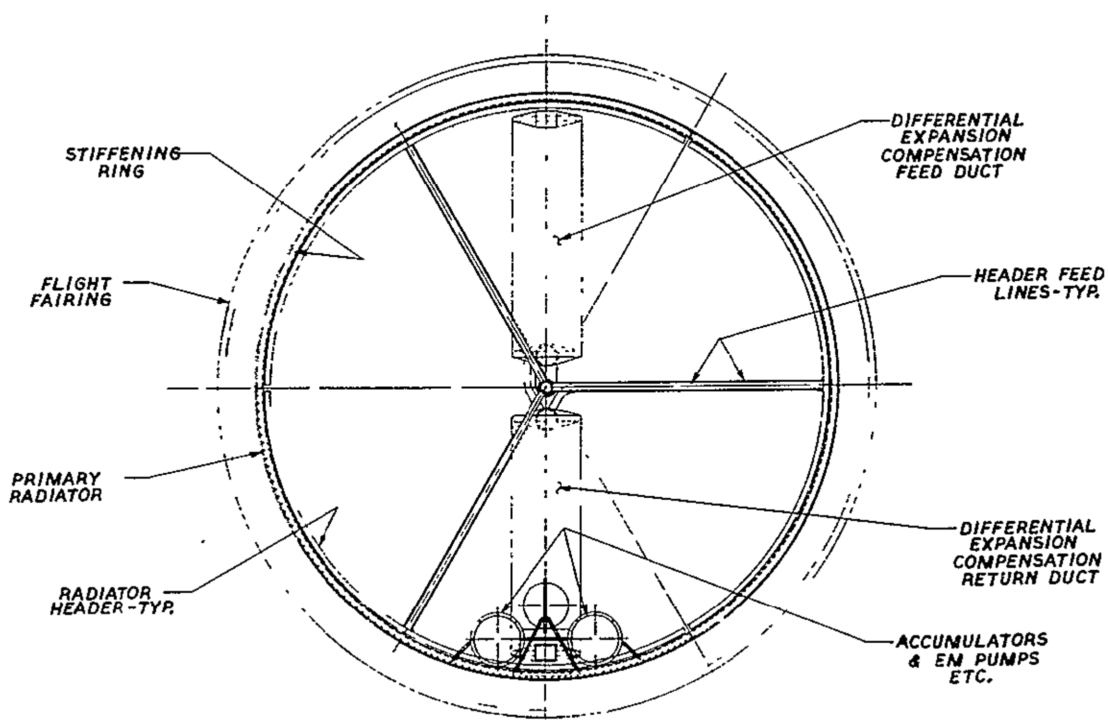

Figure 1-8. Main Radiator Cross-Sectional View, Flashlight Reactor/Spacecraft

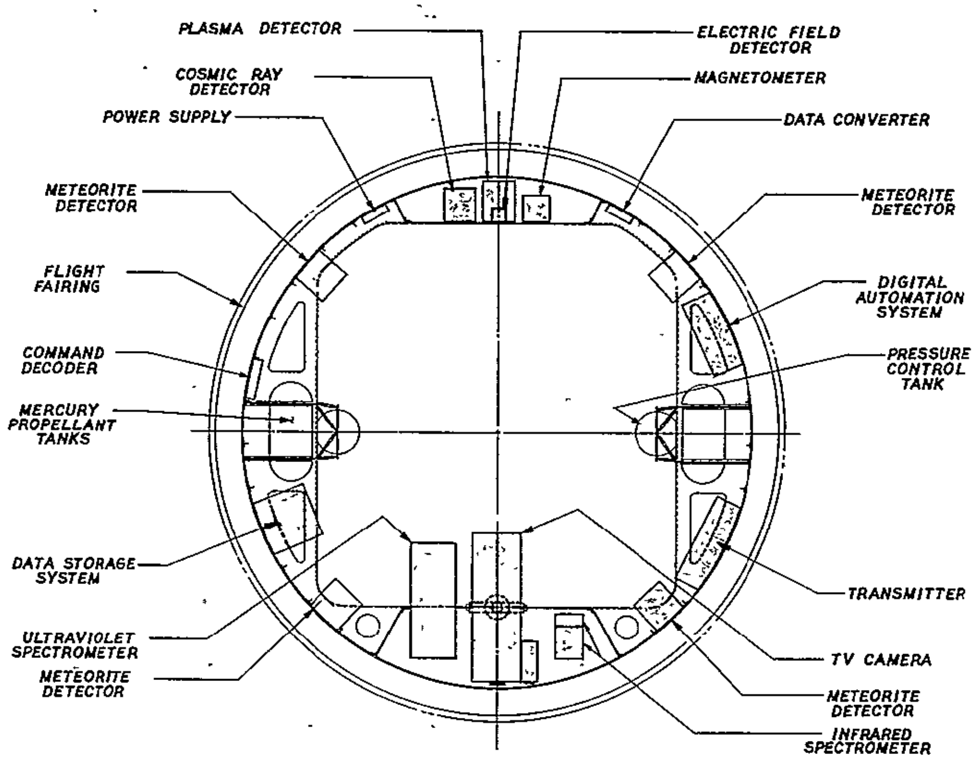

Figure 1-9. Payload Bay Cross-Sectional View, Flashlight Reactor/Spacecraft

1.3.2 WEIGHT AND POWER SUMMARY

The weight summary for the reference design spacecraft utilizing the flashlight reactor concept is presented in Table 1-4. In order to provide 240 kWe of power to the thruster system, a gross reactor power output of 318 kWe is required. Total spacecraft weight at launch is 37,605 pounds. Disposable launch vehicle adapter and payload shroud weights result in an Earth orbit spacecraft weight of 36,325 pounds.

Weight of each of the major spacecraft systems a

a. Propulsion system 19,330 pounds

b. Propellant 14,500 pounds

c. Propellant inert 260 pounds

d. Payload system 2,235 pounds

For this study, the propellant and payload systems have been defined by the study guidelines. Therefore, this design effort is devoted to configuring a weight optimum propulsion system. Summary of the key characteristics of each subsystem that comprise the propulsion system are discussed in Paragraph 1.3.3.

Electric power utilization for the flashlight reactor concept is summarized in Table 1-5. Net power to the propulsion system is 240 kWe of which 223 kWe are required for the 3100 volt screen supply operation of the ion engines, and 17 kWe are required for other special thrust power conditioning. A total of 318 kWe of reactor output power is required to meet the net 240 kWe requirement.

For purposes of mission analysis, 274 kWe (P_e) are delivered to the main power conditioning, to deliver 240 kWe to the 31 operating ion engines. This power conditioning operates at an effective efficiency of 87.6 percent, including subsequent high voltage cable and necessary ion engine isolation losses.

1.3.3 KEY CHARACTERISTICS

A summary of the key characteristics of the reference design spacecraft that utilizes the flashlight reactor is presented in this section. The shield, heat rejection, and power conditioning subsystems are discussed.

1.3.3.1 Reactor-Shield Subsystem

Neutron and gamma shielding for the flashlight reactor shown in Figure 1-5 is accomplished in the same manner as that described for the externally fueled reactor. In the spacecraft powered by the flashlight reactor there is, however, an equipment bay between the lithium hydride neutron shield and the forward tank of mercury propellant, which functions as a gamma shield. The can of lithium hydride is configured as a section of a cone, with a mean diameter of 48 inches and thickness of 26 inches. Total weight of the neutron shield is 1610 pounds.

Adequate gamma shielding is provided by 10,800 pounds of mercury propellant in the forward section. The conically shaped propellant tank is 9 inches thick with a mean diameter of 56 inches.

TABLE 1-5. ELECTRIC POWER SUMMARY 240 kWe (NET)
THERMIONIC SPACECRAFT (FLASHLIGHT REACTOR)

	POWER - kWe					
Reactor Output						318
Losses and Distribution						
Low voltage cable loss					20.5	
Main P. C. input					297.5	
P. C. loss				35.32		
Main P. C. output				262.18		
3100 volt output			224.53			
Cable losses		0.28				
Thrust interrupter		1.25				
Thrust engine input		223				
250 volt output			37.65			
Payload and ion engine section		19.3				
Cable losses	0.3					
Thrust P. C. input	17.0					
Payload input	1.0					
Spacecraft control input	0.5					
Powerplant control input	0.5					
Hotel load section		18.35				
Cable losses	0.19					
P. C. losses	2.71					
Reactor pump input	8.06					
Radiator pump input	6.5					
Shield pump input	0.16					
Auxiliary pump input	0.03					
Reactor controls input	0.2					
Cesium heater input	0.5					
Net Power to Ion Engines*						240

*The net power to the ion engines is the sum of the ion engine grid power input (223 kWe), after power conditioning, and the special ion engine power requirements (17 kWe).

The increased gamma and neutron shielding requirement for the flashlight reactor, compared to the externally fueled reactor, is due primarily to the shorter distance between the flashlight reactor and the radiation sensitive power conditioning units.

The total heating rate in the shield subsystem is approximately 1.8 kW with most of this heat being deposited in the front one-foot thickness of the neutron shield. This heat is removed by the auxiliary cooling loop.

The reactor loop piping traces a helical path just below the lateral surface of the neutron shield. The resultant holes in the shield barrier are covered with plugs of canned lithium hydride on the front end and rear faces of the neutron shield. Similar plugs of tungsten, 3.5 inches thick and weighing 265 pounds, cover the voids through the mercury tank caused by the passage of the radiator loop piping.

1.3.3.2 Heat Rejection Subsystems

The main radiator, which dissipates reactor waste heat to space, is located in the aft end of the spacecraft. As a result of the coolant activation analysis, two separate NaK-78 cooling loops, joined in series by a heat exchanger are required. EM pumps and accumulators a: included in the reactor side loop, as well as the main radiator side loop. Design of the EM pumps and accumulators is similar to that for the externally fueled reactor/spacecraft. Also, bellows in the input and return feed lines compensate for expansion among the individual bays of the main radiator.

The heat exchanger is a tube and shell, counter-cross flow unit with the hot reactor NaK-78 coolant flowing inside the tubes and the cooler radiator NaK-78 coolant across and counter to the tube flow. Weight of the dry heat exchanger is 180 pounds.

The main radiator has a total area of 945 square feet divided into 4 axial bays with three panels per bay. Each panel covers one-third of a cylindrical lateral surface (120° of arc) and is 9.8 feet wide and approximately 9 feet in axial length. Sixty-five coolant tubes, which run the length of each panel, are joined by solid fin sections of copper-stainless steel construction. The total weight of all panels plus their headers is 2190 pounds. Total weight of the primary heat rejection system is 4840 pounds.

The auxiliary cooling loop provides a thermal heat rejection mechanism for those system components which have temperature limitations lower than the temperatures in the main heat rejection system and higher than the electronic components in the spacecraft. These intermediate components are the electrical and magnetic sections of the EM pumps, and the neutron shield. Self cooling EM pumps force the NaK-78 coolant through cooling passages in the reactor EM pump electrical section, through cooling passages in the frontal regions of the neutron shield, and through the auxiliary radiator. The cooled flow is then circulated through the cooling passages of the radiator loop EM pump and returned to the auxiliary pump to complete the circuit. Accumulators control the expansion and pressure level of the coolant as in the main heat rejection loops.

The auxiliary radiator is a narrow band, containing a single cooling channel, attached to the 65 pound transition ring between the low temperature PC radiator and the high temperature main radiator. The radiating surface is ten square feet in area and 4.5 inches wide. Its weight is approximately 20 pounds. Total weight of the auxiliary loop is 110 pounds.

1.3.3.3 Power Conditioning

The power conditioning radiator rejects the heat generated in the high voltage supply and the hotel load power conditioners. The portion of the radiator, 35 square feet, corresponding to the hotel load power conditioning waste heat generation weighs 60 pounds. The remaining radiator area, 558 square feet, is attributable to the main power conditioning. The weight of this portion is 770 pounds, based on 0.10 inch thick aluminum radiator panels.

The radiator heat loads from the special ion engine PC modules and the thruster isolation units located at the base (rear) of the spacecraft, are 1.7 and 1.25 kW, respectively. The corresponding radiator areas and weights are 36 square feet and 70 pounds for the PC modules, and 26 square feet and 50 pounds for the isolation units.

A low voltage cable assembly is a two component arrangement in series: a copper cable extending from the reactor fuel element extension to the front rim of the neutron shield, and an aluminum bus bar to a power conditioning module. A low voltage cable assembly is

attached to each of the 216 reactor fuel elements. Path of the low voltage cable along the spacecraft and the power conditioning equipment is shown in Figure 1-5. Because of the low voltage (14 to 16 volts) transported by the cable and resultant high I^2R power losses, the power conditioning radiator with attached modules was located at the forward end of the spacecraft. One hundred and eight power conditioning modules, constituting the high ion engine screen grid (3100 volts) and medium hotel load (250 volts) power supply, are distributed on the inner surface of the power conditioning radiator panels. The integrated high/medium voltage supply power conditioning modules weigh 2640 pounds.

The high voltage cable subsystem consists of the 3100 volt lines between the main power conditioning modules and the ion engines and the 250 volt lines between the main power conditioning modules and the hotel load, special payload and thrust power conditioning modules.

The 3100 volt cabling consists of four separate wires forming two complete circuits. The extra circuit provides greatly increased reliability with negligible penalty. The cable starts at the rear end of one side panel of the PC radiator, runs forward the entire length of that panel, then returns down the length of an adjacent panel. This procedure, picking up the output power of all the main PC units, occurs across the six side panels of the PC radiator. The cable then traverses the axial length of main radiator and payload sections to reach the ion engines.

The 250 volt line to the payload and thruster PC modules is of similar 4 strand construction and follows the same path. The level of 250 volts was selected from the moderately high voltage line because of the rather low I^2R power losses and its convenience in designing hotel load power conditioning equipment compared to the low voltage (14 to 16 volts) cable. Difficulty of power handling and of power conditioning component selection precluded use of 3100 volts for these lines.

The power plant electric system consists of the hotel power conditioning units, and their radiators, plus the cabling to the pumps and equipment using the power. The special power

conditioning modules convert a 250 volt input power to the voltages required for the EM pumps and the reactor controls. Total hotel power conditioning weight is 185 pounds.

1.4 COMMON PARAMETERS

To aid in the design of the thermionic spacecraft and the comparison of the two propulsion systems, whose characteristics have been summarized in Subsections 1.2 and 1.3, a group of mission and component parameters which are common to both reactor concepts has been established. The following basic study ground rules define the mission objectives and remain constant throughout the study:

- Mission Definition - 600 day, unmanned Jupiter orbiter mission.
- Launch Vehicle Interface - Spacecraft initial mass in earth orbit of 30,000 pounds to be placed in 750 nautical mile circular orbit by Titan IIIC/7.
- Payload - 2205 pounds based on Navigator studies and the Mariner program.
- Thrust - 37 mercury ion engines (including 6 spares), weighing 1233 pounds, based on current technology.
- Reactor Lifetime - Full power reactor operating time is 12,000 hours.
- Propellant - 14,500 pounds of mercury propellant is required to accomplish mission.
- Radiation Limits - The integrated neutron flux shall not exceed 10^{12} nvt for neutron energy levels > 1 Mev; the integrated gamma dose shall not exceed 10^7 rads.
- Maximum power conditioning temperature of 200°F.
- NaK-78 coolant in all active coolant loops.
- Stainless steel coolant containment material.
- Copper-stainless steel material for active radiators.

Furthermore, common characteristics identified in this study for the externally fueled reactor concept and the flashlight reactor power plants are listed below:

- Sink Temperature - approximate mean sink temperature for entire mission is $300^{\circ}R$
- Aluminum material for passive radiators
- Active shield cooling mode
- No parallel cooling loops
- One working and one redundant pump in each cooling loop
- Maximum shield temperature of $1000^{\circ}F$
- Reactor controls power requirement of 0.2 kWe
- Cesium reservoir power requirement of 0.5 kWe

2. INTRODUCTION

2. INTRODUCTION

A design study program of thermionic reactor power systems for nuclear electric propelled, unmanned spacecraft was performed by the General Electric Company Nuclear Systems Programs* in the period February 4, 1969 through June 30, 1970 for the Jet Propulsion Laboratory** under Contract Number JPL 952381. The purpose of this program is to provide designs of selected thermionic reactor power systems integrated with nuclear electric unmanned spacecrafts over the range of 70 to 500 kWe unconditioned power. The key design objective is a weight of 10,000 pounds, including reactor, shielding, structure, radiators, power conditioning, and thruster subsystems at a 300 kWe unconditioned power level. Spacecraft propulsion will be provided by mercury electron bombardment ion thruster engines.

The design study is performed in two consecutive phases:

a. Phase I - Design of unmanned spacecraft and powerplant configurations, including powerplants with emphasis on state-of-the-art technology. Key ground rules include:

   1. 300 kWe unconditioned power
   2. NaK-78 coolant
   3. 1350°F reactor outlet temperature
   4. Copper-stainless conduction fin radiators
   5. Radiator non-puncture probability is 0.95
   6. 200°F maximum electronic component temperature limits
   7. 10,000 pounds powerplant weight (design objective)
   8. 10,000 to 15,000 full power hours

* Program Manager, W. Z. Prickett
** Technical Monitor, J. F. Mondt

b. <u>Phase II</u> - Emphasis on weight reduction techniques and the investigation of the effect of key parameters on power performance:

1. Coolant: substitution of lithium for NaK-78

2. Radiator non-puncture probability is 0.99

3. Radiator type: the use of beryllium/stainless steel or vapor fin radiators

4. Radiator type: the use of vapor chamber and heat pipe radiators

Two spacecraft designs were completed, based on the externally fueled diode thermionic reactor, utilizing reactor data supplied by the Republic Aviation Division of the Fairchild-Hiller Corporation, and a flashlight thermionic reactor, utilizing reactor data supplied by Nuclear Systems Programs of the General Electric Company. These two spacecraft designs are based upon the results of a spacecraft weight optimization computer code which was developed during the Phase I of the study (Reference 7). The scope of the designs presented includes detailed spacecraft layouts, and detailed weight summaries, including a discussion of the major causes for weight differences between the two spacecraft based on different reactor designs.

This report also presents the study design guidelines, including the definition of the reactors, the payload and the ion engines. Launch vehicle capabilities are discussed and structural requirements are defined. A discussion of shield analysis and electric power processing design precedes the detailed design definition of the two spacecraft.

Some preliminary results in the Mission Operations area are presented, including powerplant startup, pre-launch operations, and aerospace nuclear safety.

Weight reduction technique associated with higher temperature power conditioning (above $200^{\circ}F$), substitution of lithium for NaK-78 as the reactor coolant, and the use of Be/SS radiators in place of Cu/SS radiators are discussed. The effect of unbonded TFE trilayers on powerplant weight is evaluated for the flashlight reactor. The effect of increasing the radiator survival probability from 0.95 to 0.99 is assessed. The use of heat pipe radiators is investigated.

3. STUDY GUIDELINES

3. STUDY GUIDELINES

Program guidelines have been identified for the design study of a thermionic reactor powered spacecraft. System requirements and subsystem definition that comprise the established guidelines are presented in the following sections.

3.1 SYSTEM REQUIREMENTS

System requirements that have been defined for this study are summarized below:

a. Reference powerplant shall provide 10,000 to 15,000 effective full power hours at a nominal 300 kWe gross reactor unconditioned electric power output.

b. The spacecraft system shall be designed for launch by the Titan IIIC/7, and shall be compatible with the launch environment of this vehicle.

c. The reference point for the launch vehicle/spacecraft interface shall be 30,000 pounds delivered into a 750 nautical mile circular orbit.

d. The reference mission is a Jupiter planetary orbiter. Starting from the 750 nautical mile circular orbit, the 30,000 pound spacecraft will spiral away from earth (~50 days) and begin the trip to Jupiter. The following times and power levels are applicable:

Mission Mode	Power Level (kWe)	Time (days)
Initial Thrust	300	210
Coast	30	120
Final Thrust	300	270
Jupiter Orbit	30	(one orbit, 17 days minimum)

e. The meteoroid model will be compatible with the following models:

1. Penetration Model

$$t = 0.5\ m^{0.352}\ \rho m^{1/6}\ v^{0.875}$$

where

t = armor thickness, cm

ρ_m = meteoroid density, gm/cm^3

m = meteoroid mass, gm

v = meteoroid velocity, km/sec

2. Meteoroid Flux

$$\Phi = \alpha m^{-\beta}$$

where

Φ = cumulative meteoroid flux, number particles/m^2 sec

α = empirical coefficient

β = empirical exponent

m = meteoroid mass, gm

3. Probability of Penetration

The non-puncture probability is,

$$P_{(O)} = e^{-\Phi A T}$$

where

$P_{(O)}$ = non-puncture probability

Φ = cumulative meteoroid flux, number particles/m^2 sec

A = projected vulnerable area of the spacecraft (radiator), m^2

T = exposure time, seconds

The baseline data listed below is used in conjunction with the previous models to calculate an equivalent near earth meteoroid protection requirement:

$$\bar{\rho}_m = 0.5 \text{ g/cm}^3$$

$$\bar{v} = 20 \text{ km/sec}$$

$$\alpha = 6.62\ (10)^{-15}$$

$$\beta = 1.34$$

$$P_{(O)} = 0.95$$

$$T = 7.2\ (10)^7 \text{ sec } [20,000 \text{ hr}]$$

Then, an effective thickness, t_{eff}, for the Jupiter orbiter may be calculated from

$$t_{eff} = 0.432\ t \text{ (Jupiter)}$$

The radiator models used in this study have been developed from the SPARTAN III computer code (Reference 1) results and are based on the preceding near earth meteoroid protection requirement.

f. The reference design shall be based on:

1. NaK-78 coolant at 1350°F reactor outlet temperature

2. Electromagnetic pumps

3. Payload, power conditioning, and communications shielded to 10^{12} NVT > 1 mev, and 10^7 rad γ. Credit should be taken for attenuation from nonshielding materials.

4. 14,500 pounds of mercury propellant

5. A stainless-steel tube, copper fin, nondeployable radiator.

g. Power Conditioning

1. The power conditioning concepts identified in the reactor design studies will be evaluated and power conditioning systems will be defined which meet system requirements. Power conditioning module temperature is not to exceed 200°F.

2. Reactor control concepts will be those specified by the reactor contractors. The externally fueled reactor is controlled by maintaining constant voltage; whereas, the flashlight reactor is controlled by maintaining constant emitter temperature.

h. Payload and Communications

1. The total payload and communications system will be assumed to weigh 2200 pounds.

2. The total power requirement for this system is assumed to be one kWe. Electrical component temperature limit is 200°F.

i. Since reliability of individual components is unknown at this time, a reliability goal will not be established for the spacecraft. Emphasis will be placed on suitable configuration, light weight, careful design, and good engineering judgement.

Calculations were performed to define preliminary estimates of powerplant component weights and weight distributions. These baseline concept estimates are required for evaluation of spacecraft structural requirements, selection between one main coolant loop versus two series coolant loops, and radiator configuration studies. In addition to the above system requirements, the design is based on the following assumptions:

a. A bonded wet cell trilayer diode reactor (13 percent reactor efficiency, 2010 kW reactor heat rejection) (at the direction of JPL).

b. An allowable power conditioning and payload electronics temperature level of 200°F; a corresponding radiator temperature of 175°F.

c. Sink temperature is 300°F (approximate average for the entire mission).

The details of this analysis have been previously reported (Reference 3) and the results are summarized in Section 10, Conclusions, items 2 through 9. These results are basic to the spacecraft designs summarized in Section 1.

3.2 SUBSYSTEM DEFINITION

Characteristics of the externally fueled and flashlight reactor concepts have been provided by the reactor contractors. Also, characteristics of the thruster, science payload, communications, and thermal control subsystems have been identified; these systems are common to each of the thermionic reactor spacecraft concepts.

3.2.1 REACTOR DEFINITION

This study is directed toward the evaluation of the impact of two reactor types on the spacecraft configuration and weight. Under study by two separate contractors, these reactors are:

a. Externally fueled diode/Fairchild Hiller(Reference 4)

b. Flashlight/General Electric (tri-layer, Reference 5)

These different reactor configurations are illustrated in Figures 3-1 and 3-2, respectively.

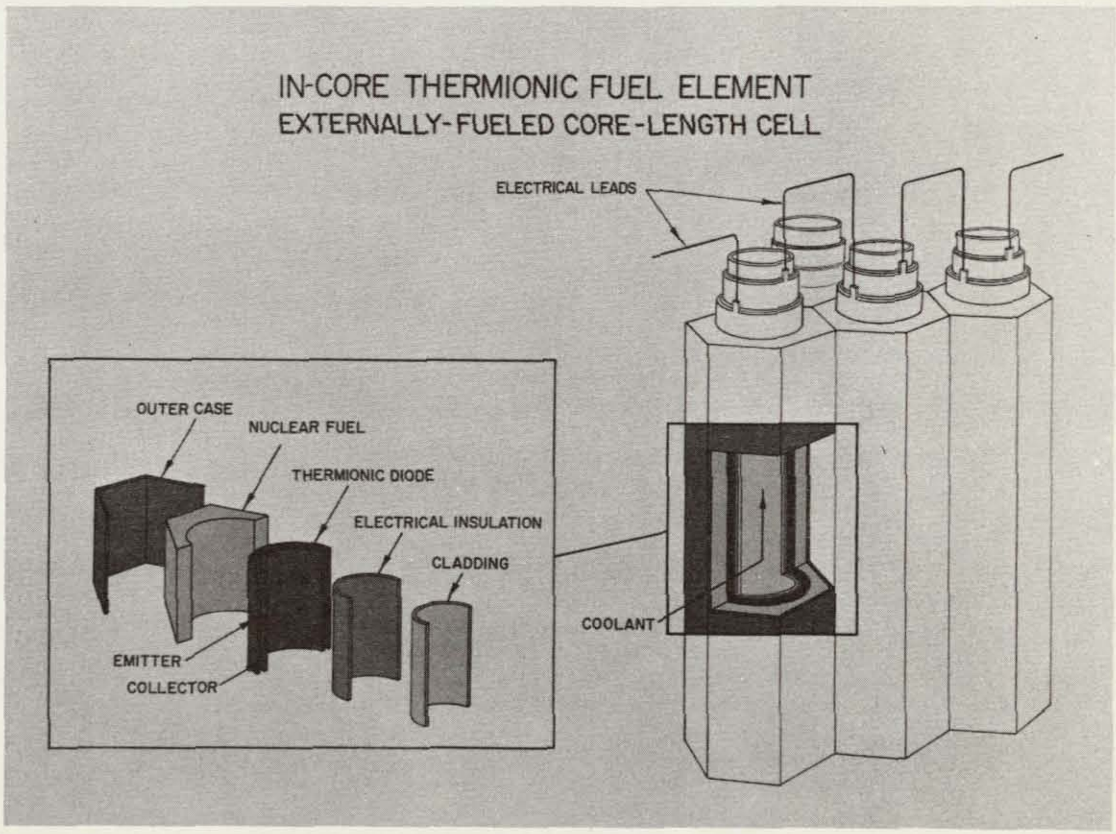

Figure 3-1. Externally Fueled Diode Reactor Concept

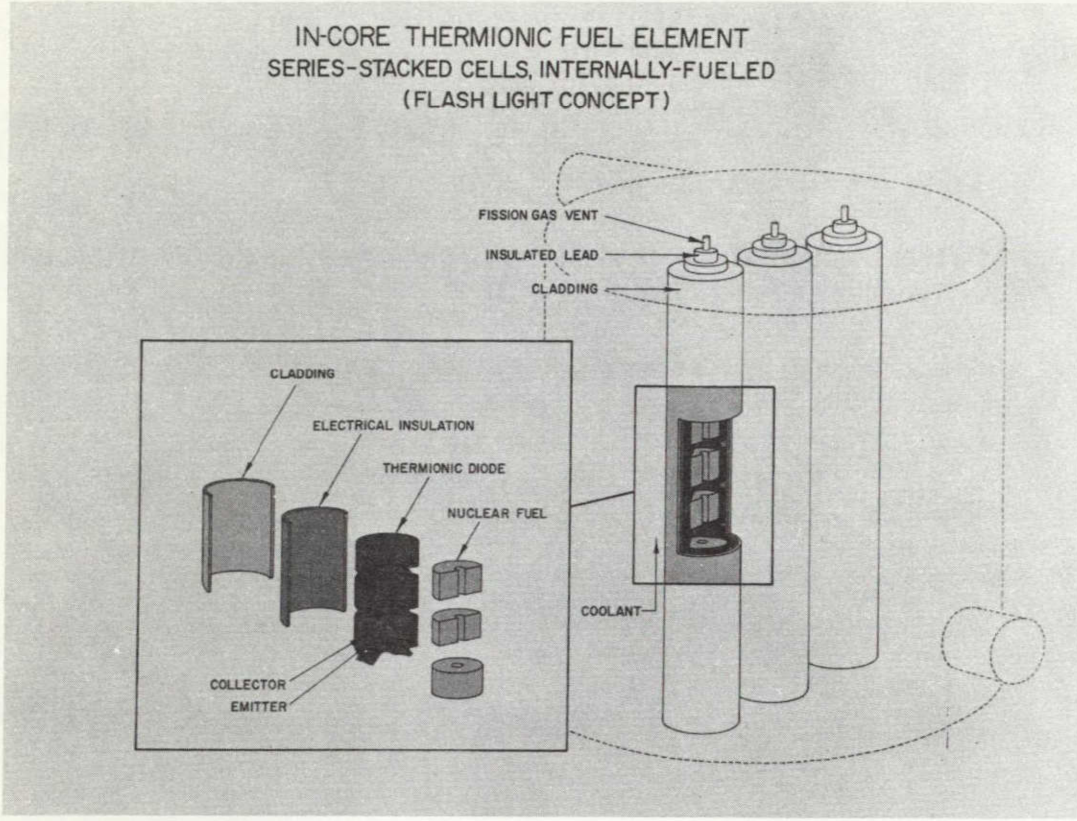

Figure 3-2. Flashlight Reactor Concept

The contractors were requested to provide definition of reactor characteristics for this study, based upon the USAEC funded studies defined by Reference 4 and 5.

Additional reactor information was requested. The data presented below was supplied.

3.2.1.1 Externally Fueled Diode Reactor

The basic element of the Fairchild Hiller thermionic reactor is the converter module. Each module consists of a fuel element which surrounds a cylindrical emitter. Coaxial with and inside the emitter is the cylindrical collector separated from the emitter by a 10-mil gap. Inside the collector is the liquid metal coolant. The module configuration is different from other designs in that the fuel is external to the emitter. This geometry allows the maximum fuel volume fraction in the core.

The externally fueled reactor consists of 624 fueled converter modules, configured in an essentially cylindrical reactor core. The diodes are arranged in a triangular lattice with a uniform center-to-center distance of 1.33 inches. The cylindrical modules are separated by 0.060-inch vacuum gaps.

The maximum emitter temperature in the reactor is 3270^{o}F (1800^{o}C) and the cesium reservoirs operate at 675^{o}F. The NaK coolant nominal flow rate is 234 gpm, corresponding to an average velocity of 6.5 ft/sec and a core pressure drop of 0.53 psi. The collector temperature varies from 1096^{o}F to 1404^{o}F.

The emitter power density varies from 8.53 to 8.64 watts/cm^{2}. Around the periphery of the core are heat shields, a radial reflector, control drums, and structure. Axially there are the emitter leads, series leads, coolant plenums, and support structure.

The 624 converters in the core are arranged electrically into 156 series-connected groups, each consisting of four converters in parallel, one from each ring. The reactor is designed for an unconditioned power output of 332 kW at beginning-of-life. Assuming 10 percent converter failures (20 percent power degradation), this yields an end-of-mission conditioned power of 240 kW at the electric thrusters.

The baseline reactor design produces 300 kWe gross at the end of mission. Only about 274 kWe gross are required to provide the 240 kWe required by the thrusters. The reactor characteristics for both the 300 kWe gross, and for the 274 kWe gross are presented on Tables 3-1 and 3-2, respectively. The data on these tables are taken from the computer printout sheets supplied by Fairchild-Hiller for this study. Details may be found in Reference 3.

3.2.1.2 Flashlight Reactor Characteristics

The flashlight reactor utilizes twelve diodes stacked in series to form a Thermionic Fuel Element (TFE). A total of 216 TFE's are grouped together to form the active core of the nominal, 300 kWe gross flashlight reactor, as illustrated in Figure 3-2.

TABLE 3-2. EXTERNALLY FUELED DIODE REACTOR CHARACTERISTICS - 276 kWe EOM

T_o = 2073 K
T_R = 630 K
Core Height = 10 in
Reactor Height = 20 in
Output Power = 332 kw (BOM)
= 276 kw (EOM)

Coolant Outlet Temperature (F)	Coolant Temperature Rise (F)	Reactor Terminal Voltage (volt)	Thermal Power (kw)	Reactor Diameter (in)	Reactor Weight (lb)	Coolant Flow Rate (gpm)	Core Pressure Drop (psi)
1350.	250	110.12	2209.	31.94	3657.	345.	1.62
1350.	250.	121.31	2105.	32.96	3909.	326.	1.03
1350.	250.	131.62	2053.	34.37	4269.	316.	0.61
1350.	250.	142.99	2048.	36.22	4764.	315.	0.35
1350.	250.	152.92	2088.	38.46	5389.	323.	0.19
1350.	350.	107.85	2213.	31.99	3669.	247.	0.85
1350.	350.	120.77	2114.	33.06	3934.	234.	0.53
1350.	350.	132.85	2066.	34 51	4307.	228.	0.32
1350.	350.	144.22	2064.	36.39	4810.	227.	0.18
1350.	350.	152.96	2101.	38.60	5431.	232.	0.10
1350.	450.	111.31	2236.	32.28	3740.	194.	0.49
1350.	450.	122.40	2141.	33.43	4028.	185.	0.30
1350.	450.	132.40	2088.	34.91	4412.	179.	0.18
1350.	450.	146.24	2105.	36.99	4974.	181.	0.10
1350.	450.	153.59	2144.	39.23	5612.	185.	0.05

The TFE units are series connected in pairs, with the center connection grounded. Each TFE pair requires an individual power converter so that the electrical operation of each TFE can be adjusted for optimum conditions. The outputs of the 108 converters are subsequently connected in parallel to provide common electrical outputs to the loads.

The flashlight reactor data employed in this study is summarized in Table 3-3. The first column lists the parameters for the reference 300 kWe design reported in Reference 5. The basic TFE for this reference design uses an unbonded trilayer, where the interface between the insulator and the collectors of each diode is a slip fit. The remainder of the data of Table 3-3 presents the flashlight reactor characteristics under the assumption of a bonded trilayer. These data were employed in the Phase I effort. The Phase II effort assessed the effect of the unbonded design on the spacecraft performance (see Section 8). Further details have been reported in Reference 3.

The various alternate designs presented in Table 3-3 provide the capability to assess the impact of various reactor operating points on the spacecraft performance. Reactor parameters varied include coolant temperature rise, coolant exit temperature, coolant pressure drop inside the reactor, and their effect on reactor weight and dimensions. These data were employed to develop a model for use in the spacecraft weight optimization computer code.

Past studies have shown that a nominal 1-inch TFE is close to the optimum diameter for this power range. No attempt was made to vary TFE diameter for these studies. The basic core arrangement was not changed for any of the alternate designs.

Studies indicate that a fixed electric output from a fixed number of diodes leads to an optimum emitter temperature distribution. If the emitters are run too hot, the maximum efficiency point is passed. If the emitters are run too cool, the current density increases, forcing increased losses on the electrical system. The value of 1950°K selected for the reference design is very near optimal for the 300-kWe configuration, with 216 TFE units, each with 12 diodes. Recent improvements in analyses indicate that it is in fact possible

TABLE 3-3. PERFORMANCE OF 300 kWe FLASHLIGHT REACTOR DESIGNS

Parameter \ Alternate	Base Design AEC Study	Alt. No. 1 1000°K (1350°F) Outlet		Alt. No. 2 868°K (1100°F) Outlet	Alt. No. 3 1145°K (1600°F) Outlet	Alt. No. 4 200°K Core ΔT	Alt. No. 5 6.8 psi Reactor Δp
TFE	Unbonded	Fully Bonded		Fully Bonded	Fully Bonded	Fully Bonded	Fully Bonded
TFE Diameter, in.	1.02	1.02		1.02	1.02	1.02	1.02
Number of TFE	217	217		217	217	217	217
Number of Cells/TFE	12	12		12	12	12	12
Core Structure	SS	SS		SS	SS	SS	SS
Coolant	NaK-44	NaK-78		NaK-78	NaK-78	NaK-78	NaK-78
Inlet Temp., °K	800 (980°F)	906	(1170°F)	768 (920°F)	945 (1420°F)	806 (990°F)	906 (1170°F)
Outlet Temp., °K	900 (1160°F)	1006	(1350°F)	868 (1100°F)	1045 (1600°F)	1006 (1350°F)	1006 (1350°F)
Reactor, Δp, psi	3.1	4.5	3.7	4.5	4.5	4.5	6.8
Max. Emitter Temp., °K	1950	1915	1950	1955	1955	1955	1915
Electric Power, kWe	330	330	330	330	330	330	330
Voltage Output Power, v	14.3	12.7	15.7	12.6	12.0	12.5	12.7
Current (TFE pairs), amp.	23100	26000	21000	26300	27600	26400	26000
Thermal Power, kW	2840	2900	2470	2980	2960	2980	2900
Coolant Heat, kW min	2510	2570	2140	2650	2630	2650	2570
EOM	----	2600	2170	2680	2660	2680	2600
Reactor Weight, lb	2970	2960		2960	2960	3040	3000
Overall Length, in.	35.5	35.5		35.5	35.5	35.5	35.5
Overall Diameter, in	28.8	28.8		28.8	28.8	28.0	28.4
Flow Rate (EOM Cond) lbs/sec		64.9	54.1	66.7	66.4	33.4	64.9

10% POWER (est.)	
Max. Emitter Temp., °K	~1600
Voltage Output Power, v	12.5
Current (TFE pairs), amp	3000
Thermal Power, kW	590
Coolant Heat Load, kW	552

z

to achieve somewhat lower emitter temperature distributions for optimum conditions. The outputs of the 108 converters are subsequently connected in parallel to provide common electrical outputs to the loads.

3.2.2 ION ENGINES

Spacecraft propulsion will be provided by 31 equal size electron bombardment ion thrust engines. Mercury was chosen over other propellants because of the relatively well developed technology of mercury systems. Information concerning the weight, volume, and position requirements of the thruster subsystem has been specified by JPL. The general guidelines used to design the thrust subsystem are given in Table 3-4.

TABLE 3-4. GUIDELINES FOR THRUSTER SUBSYSTEM DESIGN

Power to the ion engines	240 kWe
True specific impulse	5000 sec
Thruster redundancy	20 percent
Attitude control	Electric propulsion
Maximum envelope diameter	10 feet
Thrust duration	12, 000 hr
Number of ion engines (includes 6 spares)	37

Six spare thrusters will bring the total to 37 units. Considering switching and power conditioning requirements, this number of spares provides one spare engine for each group of five operating engines. Switching, logic, and spare Power Conditioning Control (PCC) units can also be grouped in this way to reduce the number of possible thrust - PCC combinations. Thrust vector control will be provided by a three axis attitude control system (two axis translation, one axis gimbal). Thrust power supply requirements and subsystem weights are given in Tables 3-5 and 3-6 respectively. The thrust system design layout, which was contributed by JPL, is presented in Figure 3-3.

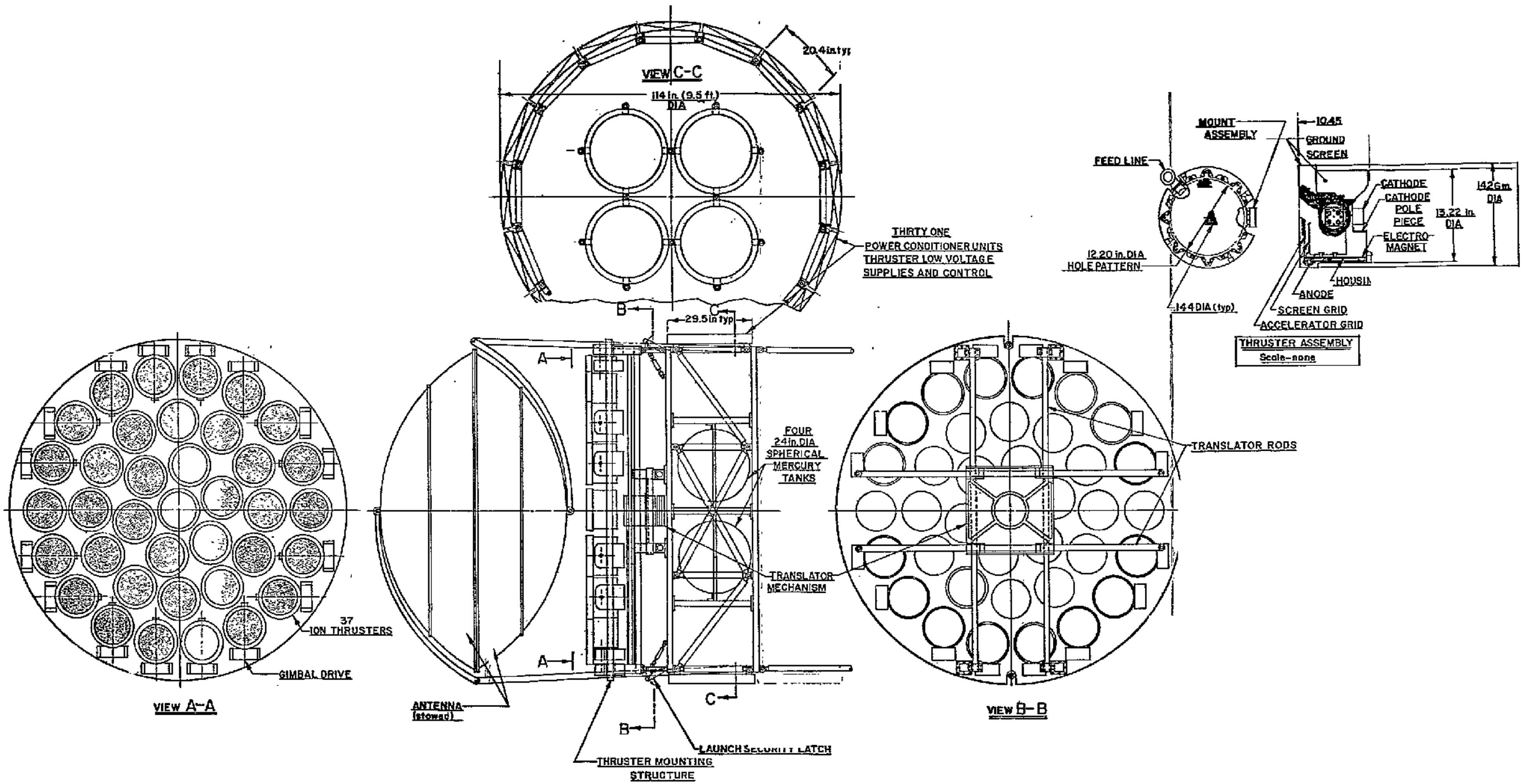

Figure 3-3. Thrust System Design Layout

TABLE 3-5. ION ENGINE POWER SUPPLY REQUIREMENTS

				NOMINAL RATING						MAX RATING		
Supply Number	Supply Name	Type	Output(1)	Volts	Amps	Watts	Reg. %	Peak Ripple	Volts	Amps	Amps Limit(2)	Control Range, A
1	Screen	DC	V	3100	2.32	7200	1.0(V)	5	3200	2.32	2.60	2.0 - 2.4
2	Accelerator	DC	F	2000	.02	40	1.0(V)	5 @ 0.2 A	2100	0.20(3)	0.21	---
3	Discharge	DC	V	35	8.3	290	1.0(V)	2	150 @ 50 mA	9 @ 37V	10	7.5 - 9.0
4	Mag - Man	DC	F	15	.7	11	1.0(I)	5	20	1.0	1.0	---
5	Cath Htr(4)	AC	F	10	4.0	40	5.0	5	11	4.4	4.1	---
6	Cath Keeper	DC	F	10	0.5	5	1.0(I)	5	150 @ 50 mA	1.0 @ 20 V	1.0	---
7	Main Vapor	AC	V	0.6	1.0	1	Loop	5	8(5)	2.0	2.2	0.5 - 1.5
8	Cath Vapor	AC	V	0.3	0.5	1	Loop	5	8(5)	1.0	1.1	0.2 - 0.8
9	Neut Cath Htr	AC	F	10	2.0	20	5.0	5	11	2.2	2.2	---
10	Neut Vapor	AC	V	0.3	0.5	1	Loop	5	8(5)	1.0	1.1	0.2 - 0.8
11	Neut Keeper	DC	F	10	0.5	5	1.0(I)	5	150 @ 50 mA	1.0 @ 20 V	1.0	---

(1) V = Variable, F = Fixed

(2) Current limit or overload trip level

(3) Current at this level for less than 5 min. at low repetition rate.

(4) Needed only during startup or until discharge reaches 3A.

(5) Startup only.

TABLE 3-6. THRUST SUBSYSTEM WEIGHTS

Component	Weight (lb)
Ion Engines	585
Thrust Vector Control System	550
Miscellaneous (wiring, adapters, etc.)	100
TOTAL	1235

3.2.3 SCIENCE PAYLOAD AND COMMUNICATION SUBSYSTEM

The general size, power requirements, and key capabilities of representative Science and Communications subsystems remain to be firmly defined for a Jupiter orbiter mission. The major guidelines to be used in the selection of these systems are:

- The total electric power available to the science payload and communications subsystems is one kWe.
- The total weight allocated to the science payload and communication subsystems (including thermal control radiators for these subsystems) is one metric ton.

A preliminary assessment was made early in the study (Reference 3)

4. LAUNCH VEHICLE

4. LAUNCH VEHICLE

The Titan IIIC/7 launch vehicle is defined as the reference booster for placing the spacecraft into a 750 nautical mile (design objective) circular earth orbit. This vehicle is similar to the Titan IIIF except that it uses a standard transtage. It is a nonmanrated vehicle and employs the stretched Stage I tanks and seven segment, 120 inch diameter solids characteristic of the Titan IIIM. The overall length of the vehicle to the payload separation plane is approximately 117 feet.

4.1 REQUIRED LAUNCH VEHICLE MODIFICATIONS

For a payload that requires a 35 foot fairing length, the launch probability on an arrival basis is 99 percent with a worst quarter probability of 95 percent. As fairing length increases to 60 feet, the arrival launch probability decreases to 75 percent with a worst quarter probability of 45 percent. To maintain this launch probability for payload fairing lengths of 60 to 80 feet, the vehicle guidance steering must be modified. Moreover, for payload fairing lengths of greater than 80 feet, modification of guidance steering and strengthening of the transtage control module skirt is required. Weight penalty for skirt revision is estimated to be 60 pounds.

4.2 FLIGHT FAIRING WEIGHT AND PAYLOAD PENALTY

During a "nominal" launch of the Titan IIIF vehicle, the flight fairing is normally jettisoned at 280 seconds, which is just after completion of the Stage I burn. In order to prevent freezing of the liquid metal coolant during launch, it may be desirable to retain the flight fairing as a radiation barrier until after reactor startup in earth orbit. However, this procedure imposes a severe payload weight penalty which depends on the shroud length (weight) and the terminal orbit altitude.

Figure 4-1 shows the flight fairing weight and the payload penalty as a function of shroud length, assuming shroud jettison at 280 seconds into the mission. If the shroud is retained past Earth orbital insertion, then the payload weight penalty will be equal to the shroud weight. It should be noted that as the terminal orbital altitude increases, the payload penalty decreases for normal shroud ejection since a larger portion of the ΔV is added after shroud ejection. The curves are based on the data supplied by the Martin Marietta Corporation (Reference 6).

The effect of shroud retention on payload capability is shown in Figure 4-2. The upper lines define the Titan IIIC/7 payload capability for a 28.5 degree orbital inclination mission with shroud jettison occurring at 280 seconds into the mission. The lower curves show the effect of retaining the shroud through achievement of final Earth orbit.

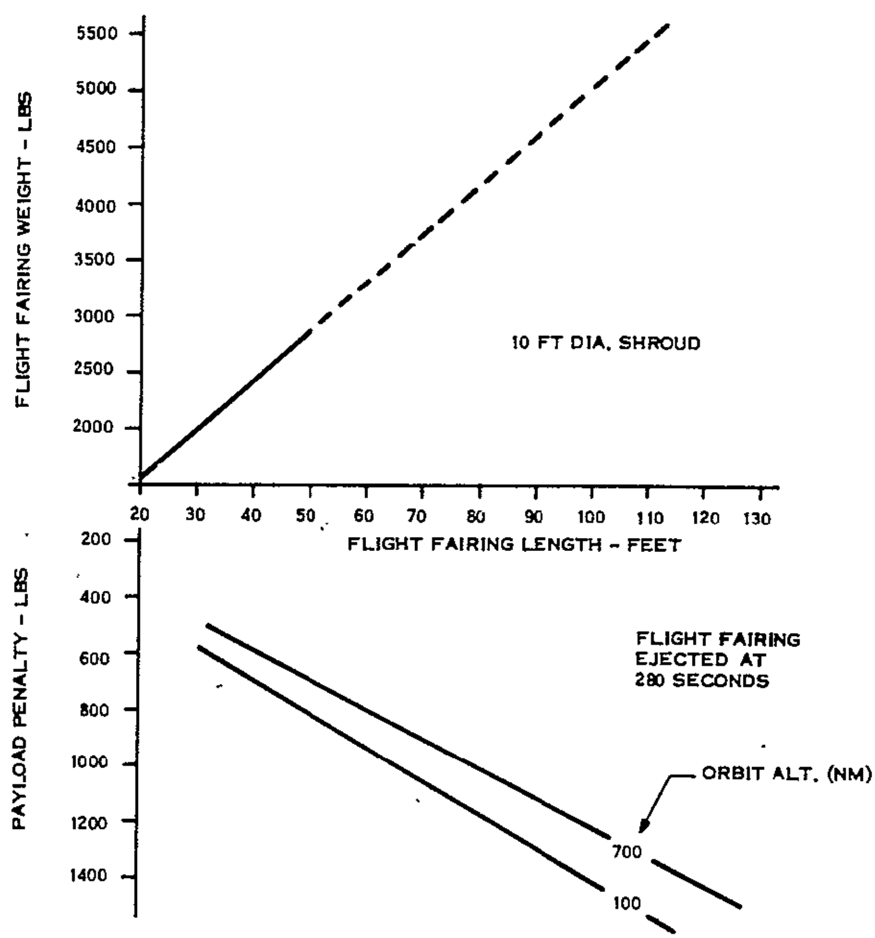

Figure 4-1. Flight Fairing Weight and Payload Penalty (Titan IIIC/

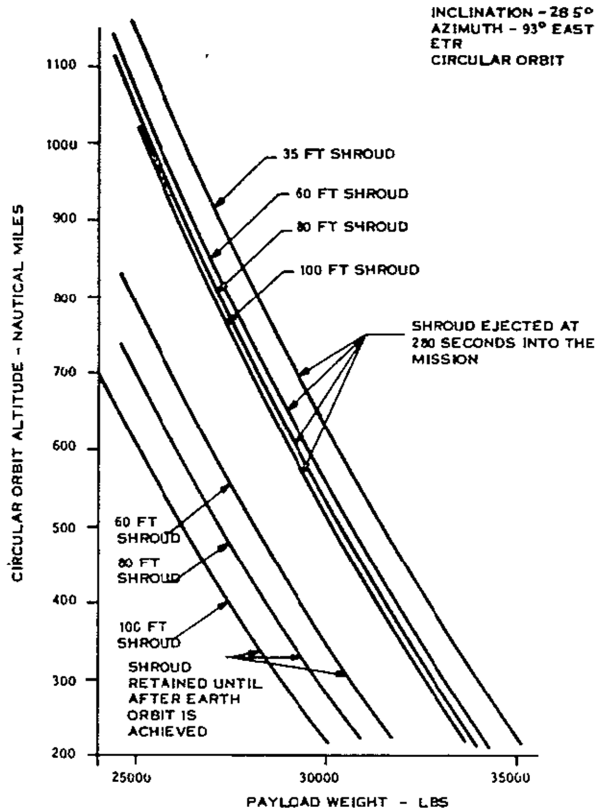

Figure 4-2. Effect of Shroud Retention on Payload Capability (Titan IIIC/7)

Under nominal conditions, and with a 35-foot shroud, the vehicle can deliver 30,000 pounds into a 630 nm circular orbit. Employing longer shrouds, with jettison at 280 seconds, reduces the payload capability (initial mass in Earth orbit) as shown in Table 4-1.

TABLE 4-1. MAXIMUM PAYLOAD CAPABILITY WITH SHROUD EJECTION AT 280 SECONDS

Shroud Length (feet)	Shroud Penalty (pounds)	Maximum Payload Weight (pounds)
60	808	29,191
80	1021	28,978
100	1234	28,765

Alternatively, injecting 30,000 pounds of payload into circular orbit will decrease the maximum possible orbit altitude as shown in Table 4-2.

TABLE 4-2. MAXIMUM EARTH ORBITAL ALTITUDE FOR A 30,000 POUND PAYLOAD WITH SHROUD JETTISON AT 280 SECONDS

Shroud Length (feet)	Maximum Orbit Altitude (nm)
60	555
80	530
100	512

If the shroud is jettisoned after achieving Earth orbit (630 nm), the payload capability will be reduced as shown in Table 4-3.

TABLE 4-3. MAXIMUM PAYLOAD CAPABILITY AT 630 NAUTICAL MILE WITH SHROUD EJECTION AFTER ACHIEVING EARTH ORBIT

Shroud Length (feet)	Shround Penalty (pounds)	Maximum Payload Weight (pounds)
60	3300	26,700
80	4200	25,800
100	5000	25,000

4.3 ALTERNATE LAUNCH VEHICLE

To provide flexibility in the selection of a launch vehicle, alternates to the Titan IIIC/7 have been examined. A moderate increase in payload capability or initial Earth orbit altitude is offered by other members of the Titan family, such as Titan IIID/Centaur and Titan IIID/7/Centaur. The Titan IIID/Centaur is similar to the Titan IIIC except

that the transtage has been replaced by the Centaur upper stage. The Titan IIID/7/ Centaur utilizes the stretched Stage I tanks and seven segment, 120 inch diameter solid rocket motors. These launch vehicles would experience even greater physical constraints than those outlined in Subsection 4.1. Consequently, launch from ETR Pad 37B, which has been used for S-IB launches, and major redesign of the universal environmental shelter would be required if a Titan launch vehicle is used.

Substantial increase in payload capability can be realized from the intermediate class of Saturn launch vehicles. For this study, the SIC/SII and SIC/SIVB configurations have been considered. Launch pad modifications would not be required if a Saturn family launch vehicle were employed.

Payload capability of the previously discussed launch vehicles are compared in Table 4-4 for circular orbit altitude of 500, 630 and 750 nautical miles. For this configuration, the payload capability of the Titan launch vehicles is based on nominal conditions and the use of a 35 foot shroud, which is jettisoned at 280 seconds into the mission. Similarly, shroud weight penalty associated with the longer thermionic spacecraft is not included in the payload capability presented for the Saturn vehicles.

TABLE 4-4. COMPARISON OF PAYLOAD CAPABILITY (POUNDS) FOR TITAN AND SATURN LAUNCH VEHICLES

Launch Vehicle \ Orbit Altitude (nm)	500	630	750
Titan IIIF	31,400	30,000	28,700
Titan IIID/Centaur	32,000	30,700	29,500
Titan IIID/7/Centaur	41,000	39,300	38,000
SIC/SII	54,000	-	-
SIC/SIVB	120,000	106,000	103,000

5. SHIELD ANALYSIS

5. SHIELD ANALYSIS

Preliminary shielding calculations were performed at the Oak Ridge National Laboratory. A one-dimensional spherical geometry mock-up of the Flashlight/Shield assembly formed the basis of the calculations. The neutron shield consisted of LiH containing 3 v/o of stainless steel, and Hg propellant was used as gamma shielding material. The shielding requirements were defined by assigning neutron and gamma dose limits at a point located 3 meters from the backface of the shield. The integrated neutron dose was to be no more than 10^{12} nvt for neutrons with energies greater than 1 Mev. The gamma dose limit was set at 10^{7} rads.

The one-dimensional spherical mock-up of the reactor/shield assembly is shown in Figure 5-1. Unlike the usual situation, the gamma shield in this case is composed of a material whose presence is independent of the need for shielding. This permits the location of the gamma shield outside of the neutron shield in the region of the lowest neutron flux, thereby minimizing the secondary gamma sources in the gamma shield. Ordinarily, this location for the gamma shield would be avoided if possible since it tends to increase the total shield weight. The dimensions shown in Figure 5-1 which locate the outer LiH and Hg surfaces were determined by the shielding calculations. All of the other dimensions were fixed input to the problem.

Although the use of the Hg propellant as gamma shielding is a welcome weight saving device, it does present some complications. In the first place, it is expended during the mission, thereby becoming a time dependent gamma shield. Secondly, only that fraction of the Hg needed to satisfy the dose limitation is to be placed adjacent to the neutron shield. The remainder of the Hg is to be located at the opposite end of the vehicle. This distribution of the Hg represents a more stable configuration at launch than one in which all of the Hg were located at the shield. Consequently, less spacecraft supporting structure is required.

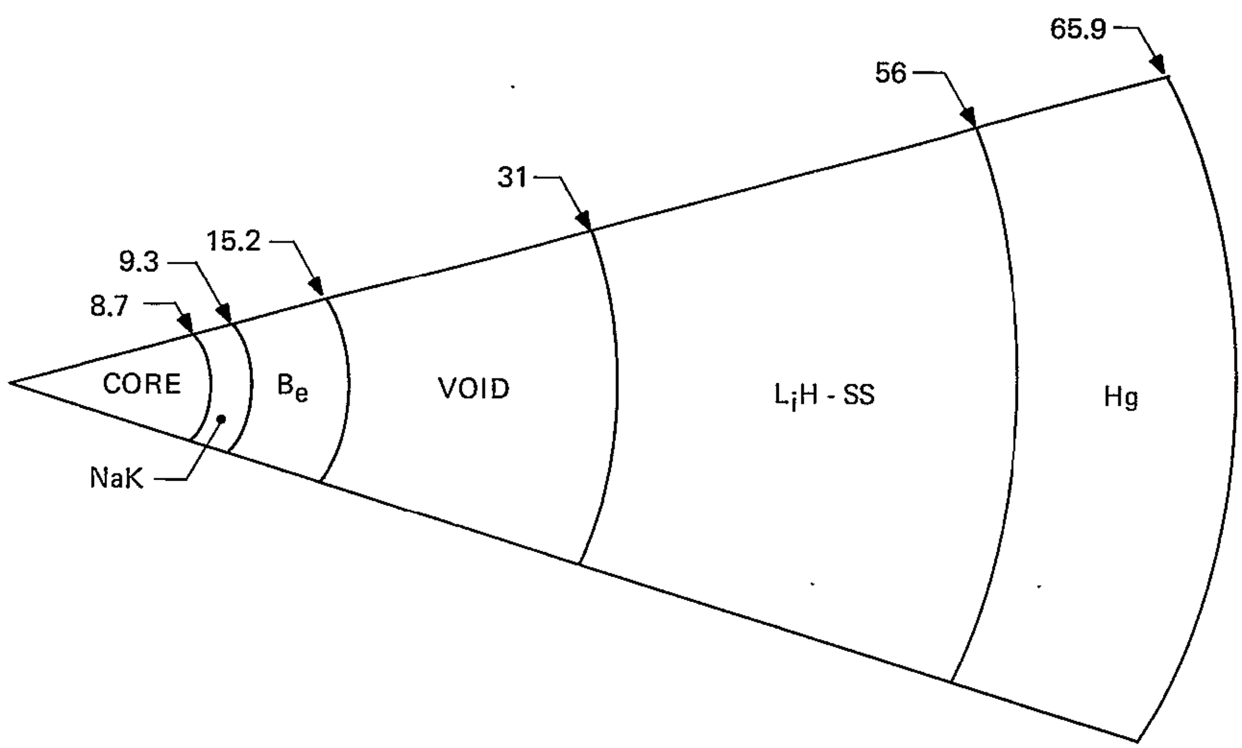

Figure 5-1. Flashlight Reactor/Shield Mockup

The time dependence of the Hg shield thickness was determined on the basis of the following conditions. The Hg propellant was to be expended during two thrust periods as indicated in Figure 5-2. In addition, it was to be expended at the same uniform rate during each thrust period. The volume of Hg used for a given gamma shield thickness would be determined by the reactor/gamma shield separation distance and the cone half angle. The separation distance depends in part upon the neutron shield thickness, hence an iterative procedure is required to determine the necessary neutron shield thickness and the time dependence of the gamma shield thickness.

Given the vehicle geometry, cone half angle and total Hg weight assigned as a basis for the shield calculations, it was found that 25 inches of LiH and an initial thickness of Hg of 9.9 inches would be required to satisfy the shielding requirements. The Hg thickness would remain constant until about 45 days into the second thrust period.

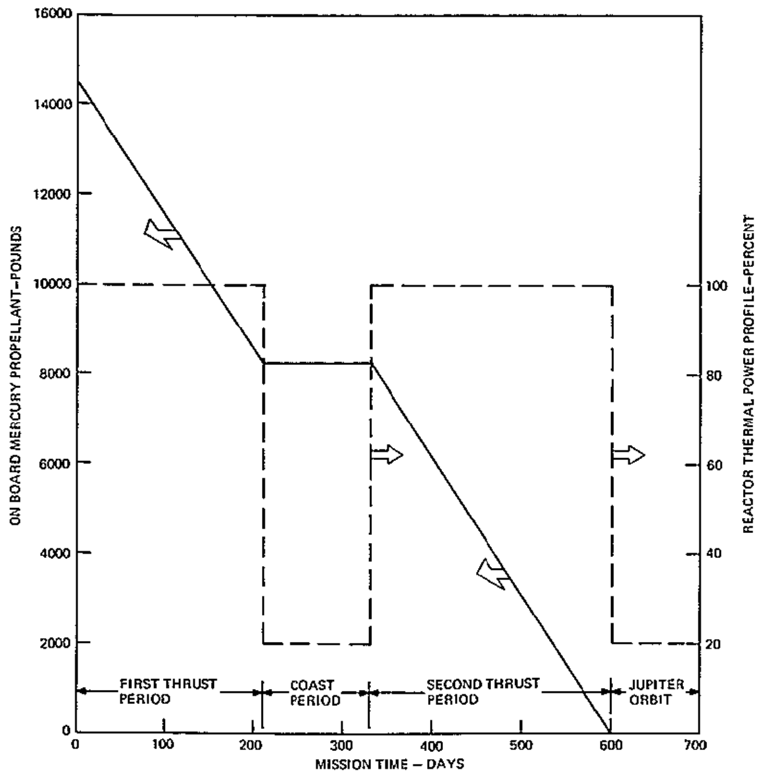

Figure 5-2. Mission Profile

From this point in time to the end of the second thrust period, the Hg thickness would decrease linearly to zero inches. Time dependent gamma and neutron dose rates have been previously reported (Reference 3).

Shielding calculations have yet to be performed for the externally fueled reactor. Hence, the data described above for the flashlight reactor have been used to aid in estimating the externally fueled reactor shielding requirements. The estimates were based upon the assumptions listed below:

a. Fluxes and dose rates at a point one meter from the Hg tank are the same for both reactor/shield assemblies

b. Angular fluxes are uniform over the outward directions at the backface of the Hg tank

c. Scalar fluxes are constant over the backface of the Hg tank

d. Attenuation of neutrons or photons by LiH or Hg could be adequately treated by fitting simple exponential functions to the curves shown in Figure 6-6.

The second and third assumptions above were used to replace the Hg tank with an equivalent disc, or surface, source located at the backface of the tank. This disk source was then used to derive an expression which describes the variation of the flux or dose rate with distance from the source. The derived expression was:

$$\phi(Z) = \phi(0)\left[1 - \frac{1}{\left(1 + \frac{a^2}{Z^2}\right)^{1/2}}\right]$$

where:

ϕ = flux or dose rate

Z = distance from the disc source along the disc axis

a = disc radius

The quantity ϕ (0) was determined by applying the first of the assumptions listed above.

6. ELECTRICAL SYSTEM DESIGN

6. ELECTRICAL SYSTEM DESIGN

6.1 INTRODUCTION

The electrical power conversion system and its components have been designed for use in each of the thermionic powered spacecraft. The baseline 300 kWe design resulted in electrical systems having the following efficiencies and specific weights:

	Efficiency (%)	Specific Weight (lb/kWe)
Flashlight Reactor Electrical System	83	14.2
Externally Fueled Reactor Electrical System	89	7.0
Dynamic Electrical Power Conversion	93	7.2

The DC/DC converters for the respective systems have characteristics as follows:

Flashlight Reactor Converter	89	9.5
Externally Fueled Reactor Converter-		
90 vdc	89	5.1
120 vdc	91	

The following sections and the Phase I report show the design detail which substantiates the estimates of size, weight, and efficiency of the electrical system for each reactor concept.

The electrical system design for the flashlight system design for the flashlight reactor system is based upon providing a DC/DC converter for each of the 108 thermionic pairs of the reactor. The outputs of these converters are paralleled forming two busses. One bus is a 3100 vdc potential for the thruster screens and the other is 250 vdc for distribution to the hotel and payloads. Individual thruster isolation is provided by SCR-reactor devices.

The externally fueled reactor electrical system is designed considering that the reactor has a single power output. Power is provided to a separate power conditioner for each thruster to develop the 3100 vdc screen potential. The hotel and payloads are supplied directly from the reactor output.

The dynamic power system uses a motor-generator to convert the 15-volt dc output from a flashlight thermionic reactor to 250 vac for hotel and payloads and for transformation to 3100 volts for the thruster screen circuits.

6.2 REQUIREMENTS/CHARACTERISTICS

The primary requirements of the electrical system are to convert the electrical power developed by the thermionic reactor power generators to forms suitable for use by the various electrical loads and to distribute the electrical power with proper protection and control.

6.2.1 BASELINE LOAD REQUIREMENTS

A tabulation of the electrical requirements of the baseline spacecraft is given in Table 6-1, and thruster power requirements are shown in Table 3-5. The main portion of the system electrical power is conditioned for the ion thruster screen grids which require about 80 percent of the thermionic reactor electrical output. A total of 37 thrusters are on the spacecraft of which 31 are active and 6 are spares. Each thruster screen requires 7.2 kW at 3100 dc.

The ion engines, which represent the principal electrical load of the system, are known to arc frequently. The system has been designed so that when arcs occur three times within a 10-second period, it becomes necessary to shut down the engine to allow the arc to extinguish and then restart the engine.

TABLE 6-1. BASELINE SPACECRAFT ELECTRICAL LOAD REQUIREMENTS

Item	Function	Power Required (kW)
Primary Loop Coolant Pump	Cools Reactor	10 kW flashlight/4 kW ext. fueled
Secondary Loop Coolant Pump	Cools Power Loop	10 kW flashlight/0 kW ext. fueled
Shield Pump	Cools Shield	0.12
Auxiliary Pump*	Cools Pumps, etc.	0.1
Propellant Pump	Pumps Mercury Prop. to Thrusters	0.1
Reactor Controls	Controls Reactivity of Reactor	2.0 (later reduced to 0.2)
Cesium Heaters	Maintains Temp. of Cesium Vapor	0.5
Thrusters	Propulsion	240.0
Payload Science	Science and Communications	1.0
Guidance and Control	Thrust Vector Control of Ion Engines	0.5
System Controls	Protection, Switching and Control of Electrical System	0.5

* If separate from shield pump

Analysis shows that even at the extreme arcing rate of 20 arcs per hour, the reduction in average load is only about 3.5 percent. Since arcing frequency tends to diminish with time, the reduction in average load by thruster arcing may be neglected.

6.2.2 REACTOR ELECTRICAL REQUIREMENTS

6.2.2.1 Flashlight Thermionic Electrical Requirements

Details of reactor electrical characteristics as well as the method recommended for reactor control are presented in References 3, 4 and 5. Reactor control is basically a constant current control loop. The electrical characteristics corresponding to load requirements during various flight phases are shown in Table 6-2.

TABLE 6-2. FLASHLIGHT REACTOR ELECTRICAL CHARACTERISTICS

	BOM(1)	EOM(2)	Coast
Electric Power, (kWe)	300	300	30
Voltage Output, (volts)	16.8	15.7	12.5
Current, (amperes)	17,900	19,100	2400
TFE Pairs	108	97(3)	108
Current/TFE Pair	165.7	196.9	23.8
Emitter Temp., Maximum (^{o}K)	1950	1950	1600

Notes:

1. Beginning of Mission
2. End of Mission
3. 10 Percent TFE pair loss at EOM

The electrical power conditioning system is to provide control of the amount of power that is extracted from each Thermionic Fuel Element (TFE) pair to ensure proper electrical and thermal balance within the reactor. The flashlight reactor is divided into six zones for analysis purposes, each with different temperature characteristics. Consequently, for TFE's in other zones, the electrical output characteristics are different. Furthermore, the TFE's throughout the reactor may also be electrically different due to construction variations.

On the basis of these requirements and the data of Table 6-2, the power conversion equipment is designed to accomodate input voltage during normal full power operation from a low of 14 volts to a high of 17 volts, and during the coast phase must accommodate an input of of 12 volts. Furthermore, since one-half of a TFE pair may fail, provisions are included for allowing the conversion equipment to operate from the remaining TFE. For power conditioner design purposes, this is assumed to be one-half voltage condition at EOM under full power.

6.2.2.2 Externally Fueled Thermionic Reactor Electrical Requirements

The selected externally fueled thermionic reactor has a nominal power capability of 300 kWe (Reference 4) and has a constant 120-volt direct current output. No need for control circuits for the thermionic diodes are defined for the power conversion system.

Reactor control is based upon neutron flux and output voltage. The reactor control circuit consists of an inner loop to control neutron density proportional to heat generation rate, and an outer loop which is slower than the inner loop, to produce incremental changes in heat evaluation to maintain constant input voltage.

6.3 BASELINE ELECTRICAL POWER SYSTEM DESIGN

6.3.1 FLASHLIGHT REACTOR ELECTRICAL POWER SYSTEM BASELINE DESIGN

The weight of the equipment for the electrical system, including transmission, distribution, and interconnecting cables, but not radiators (which are assumed to be the primary structural mounting member for the electrical equipment), is estimated to be 4491 pounds. Total electrical power losses for the system are estimated to be 52, 870 watts, for an overall efficiency of 83 percent for the basic 300-kW system. A breakdown of the principal baseline components of weight is given in Tables 6-3 and 6-4. The baseline electrical power balance is given in Table 6-5.

TABLE 6-3. ELECTRIC SYSTEM WEIGHT SUMMARY
FLASHLIGHT REACTOR SYSTEM

Component	Weight (pounds)
Main Converters	2690
Auxiliary Power Conditioning	507
Power Distribution Cables	984
Screen Supply Interrupters	310
Total	4491
Specific Weight (Load 316.2 kWe)	14.2 lb/kWe

TABLE 6-4. FLASHLIGHT REACTOR SYSTEM MAIN
CONVERTER WEIGHT BREAKDOWN

Component	Weight (pounds)
Bypass rectifiers	1.0
Input filter	
Choke	3.0
Capacitor	1.0
Inverter	
Power transformer	4.0
Transistors	1.0
Current transformer	0.25
Contactor	2.0
Base drive circuits	0.5
HV output	
Rectifiers	0.05
Filter inductor	1.5
Filter capacitor	1.5
MV output	
Rectifiers (SCR)	0.2
Filter inductor	0.5
Filter capacitor	0.5
Control circuits	0.5
Wire Brackets, Hardware, etc.	7.4
Converter Weight, (single TFE pair)	24.9
Total Weight Main Converter Flashlight Reactor System (108 TFE pairs)	2690
DC/DC Converter Specific Weight (lb/kWe out, load 282.8 kWe)	9.5 lb/kWe

TABLE 6-5. FLASHLIGHT BASELINE SYSTEM POWER BALANCE

LOSSES	WATTS	
Main Power Conditioners		
Transistor Conduction Loss (0.55 x 165)	91	
Transistor Switching Loss	25	
Transistor Base Drive Loss (3v x 165/10)	49	
Transformer (3%)	85	
Input Filter (1%)	28	
Output Rectifiers (HV)	3	
Output Filter (HV)	12	
Output Rectifiers (MV)	4	
Output Filter (MV)	2	
Control Circuits	10	
Total Losses, single TFE pair unit	309	
Total Main Power Conditioning Losses, 108 units		33,400
Screen Supply Interrupter		1,250
EM Pump Power Conditioning		3,700
Thruster Auxiliry PC*		*
Payload Power Conditioning		100
Reactor, Powerplant and Spacecraft Controls		322
Transmission Cables		14,100
Total Losses		52,872
LOADS		**WATTS**
Thruster Screen		223,000
Thruster Auxiliary Power		15,500
Payloads, Science		1,000
Guidance		500
System Control		500
Primary EM Pump		10,000
Secondary EM Pump		10,000
Shield Pump		100
Auxiliary Pump		100
Propellant Pump		100
Reactor Control		2,000
Cesium Heater		500
Total Loads		263,300
Total Power Required		316,172
Electrical System Efficiency		83%
Power Conditioning Efficiency		89%

*Losses are included in Ion Engine Efficiency

The basic electrical power system proposed for the spacecraft utilizing the flashlight thermionic reactor is shown in Figure 6-1. In this system, each TFE pair is provided with a power conversion module and each provides a medium and high output voltage level of 250 volts and 3100 volts, respectively. The outputs of each module are filtered and all modules are connected in parallel to create the two distribution power busses.

The high voltage output bus provides power to all of the screen electrodes of the ion engine thrusters. The 3100-volt level is established by the voltage requirements of the screens.

The 250-volt output provides power to the remaining spacecraft loads including the auxiliary power supplies required for each thruster as well as the hotel loads and payloads. The 250-volt potential was selected for auxiliary power distribution being relatively high voltage for cable power loss minimization, but below most corona and arc-over levels regardless of atmospheric pressure and humidity.

Power to the hotel loads and to the auxiliary thruster power supplies and the payloads is distributed by means of two 250-volt busses; one group of loads near the reactor and one at the thruster/payload area.

6.3.1.1 Main Power Converter Design

Details of the basic TFE power converter modules selected for the flashlight reactor system are shown schematically on Figure 6-2.

The individual converter design approach was used for equipment sizing for this study, since it results in the optimum design for a weight limited spacecraft. The power conversion equipment was sized for average TFE current and average TFE voltage. It should be remembered, however, that some converters may be larger and some smaller than average.

From the TFE data for the 300-kWe operating points shown on Table 6-2, it is clear that the TFE pair average current is largest at end of mission (197 amperes), and average voltage

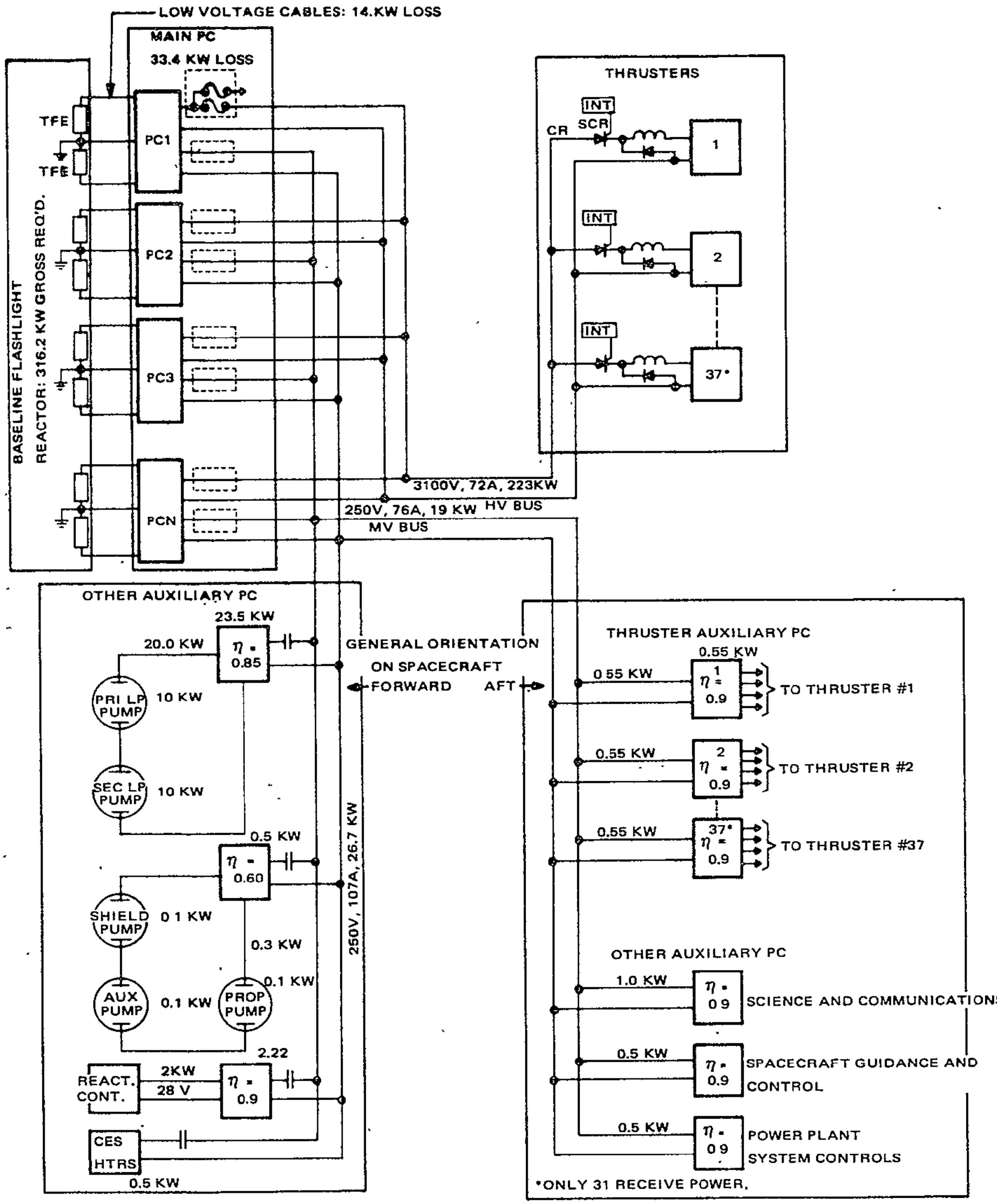

Figure 6-1. Baseline Flashlight Reactor Powered Spacecraft Electric Network

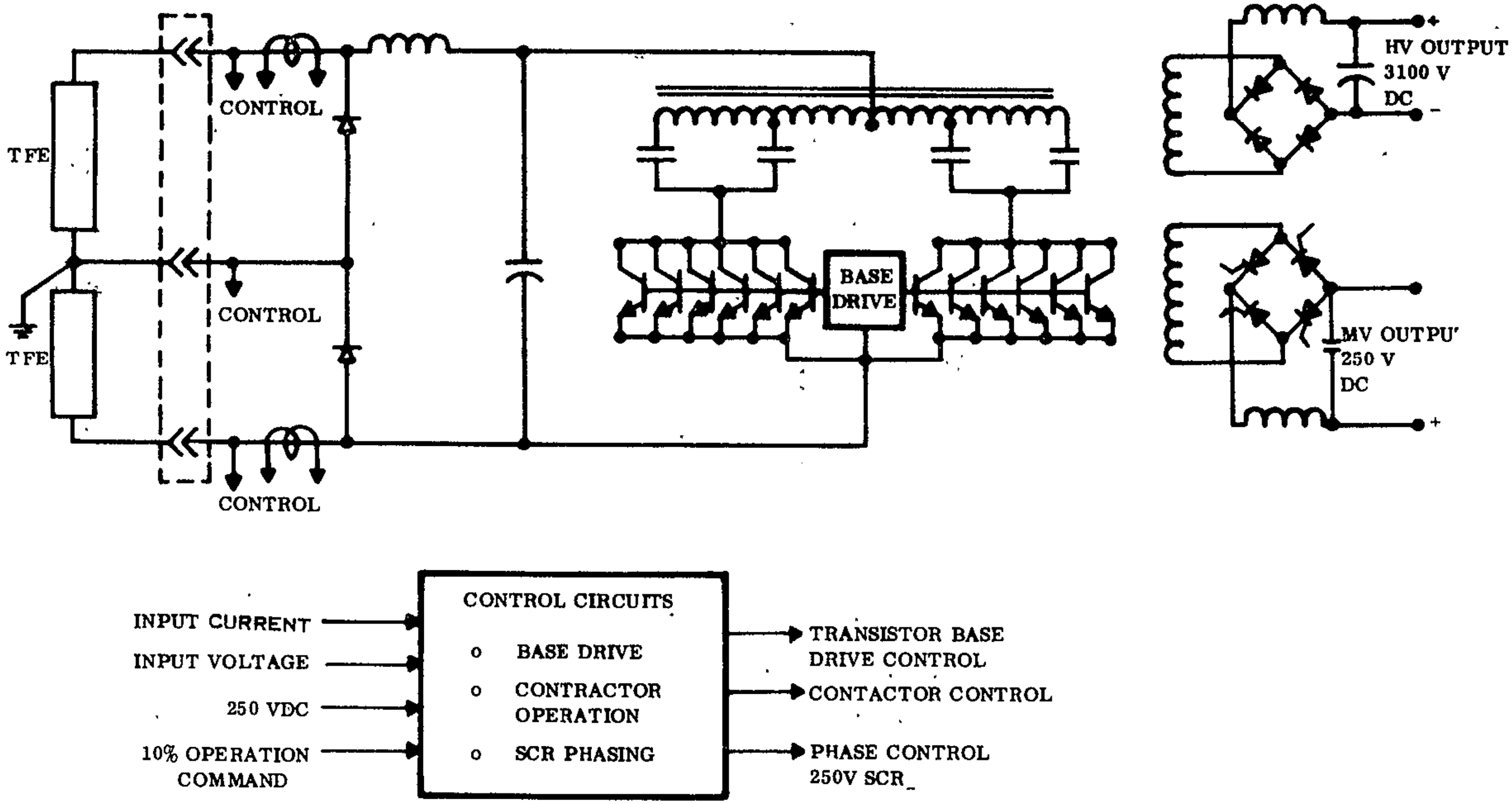

Figure 6-2. Basic Converter Module Schematic

is highest at beginning of mission (16.8 volts). The end of mission current increase when compared with beginning of mission current primarily is due to the assumed loss of 10 percent of the TFE's, and not necessarily to the characteristic change.

Over the life of the reactor, while delivering full power and excluding failure of one-half of a TFE pair, the average output voltage will range from 15.7 volts to 16..8 volts. In considering the total voltage range for which to design the primary power converters, however, it is necessary to consider also the voltage range required by the reactor current regulating control scheme. For this purpose, acknowledging that the primary users of power are the relatively constant ion bombardment engines, assume the spacecraft load can change instantaneously by 10 percent full load (30 kW). The control system described for the flashlight reactor requires that in the steady state TFE current be proportional to reactor thermal power so that emitter temperature is controlled following electrical load changes (Reference 5). Transiently, in the first few milliseconds after an electrical load, diode temperatures remain constant and diode voltage and current approximately follow the isothermal characteristic curves, as shown for example on Figure 6-3. For large load changes, the corresponding thermionic diode voltage change would be large, but for relatively small load change of concern here, the corresponding instantaneous voltage change is quite small (i.e.,) 0.8 volts which is approximately 5 percent at the operating levels). Assuming that the control system limits the total excursion to the 0.8-volt value as a maximum, then the total input voltage range, for which the conversion equipment should be designed, is from about 14 volts to about 18 volts. Additional provisions are required for operation at the failed half input voltage and the coast voltage corresponding to 10 percent power. For this range of input voltages, the output voltage should be held constant. Electrical input characteristics for the primary power conditioners design then are as follows:

Input Voltage

Full power: 14 to 18 vdc
Coast power: 11 vdc (minimum)
Half TFE failure: 7 to 9 vdc

Input Current

Full power: 196.9 amperes (maximum)
Coast power: 23.8 amperes

Maximum Input Power Rating

(18) (196.9) = 3.55 kW

6.3.1.1.1 Inverter Design Summary

For purposes of this study, power conversion equipment design is based on the following selections:

Switching devices	High speed silicon transistors (Westinghouse 1776 - 1460)
Operating frequency	10 kHz
Magnetic core material	Electrical steel such as Hymu-80
Module size	Full size for one TFE pair 196.9 amperes, maximum 11-17 volt with provisions for half voltage operation
Reliability provisions	No additional circuit redundancy

Supporting analyses has been previously reported (Reference 3).

6.3.1.1.2 Component Size Identification

A complicating factor in the use of power transistors in this application is their limited current rating compared to the total current delivered by the source. For example, the rating of the Westinghouse 1776-1460 is 60 amperes, whereas the EOM current of a TFE pair is 196.9 amperes. If the transistors are operated at 30 amperes, both to reduce the saturation collector-emitter voltage drop and to provide normal design margin for reliability (a standard JPL practice), six transistors operating in parallel are required per group. The problems associated with operating many transistors in parallel are at least twofold: proper sharing of current and coordination of turn-off characteristics, especially storage time, so that the transistors in a group all turn off together and one transistor does not carry all of the current during the switching interval.

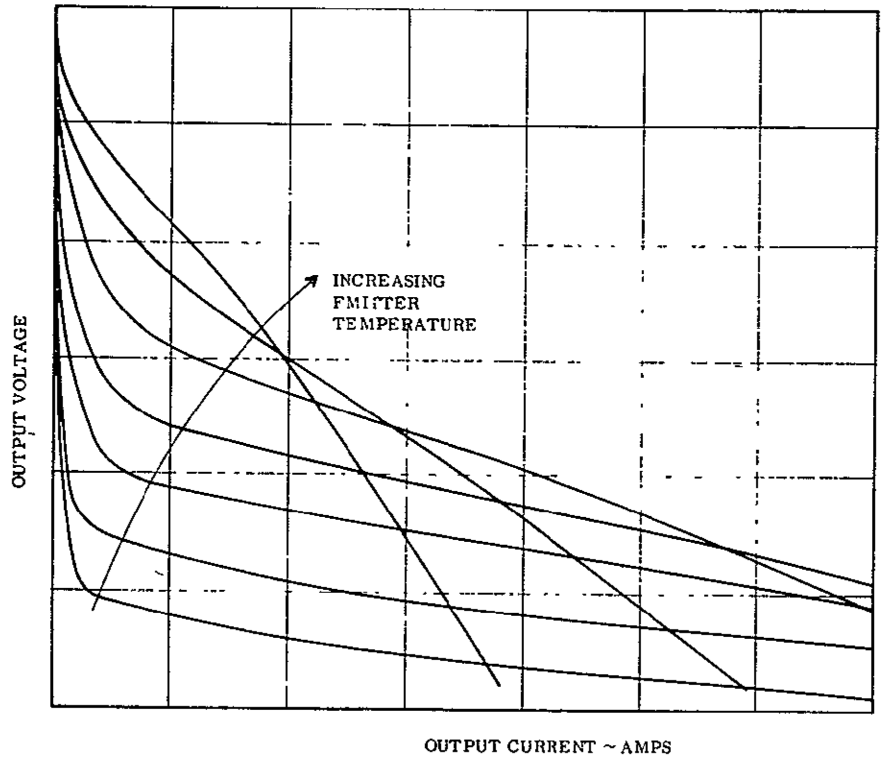

Figure 6-3. Typical Thermionic Reactor I-V Characteristics

The method with the greatest reliability considering series components is direct paralleling (Reference 3), and is selected for use in the flashlight thermionic power conditioner. Transistor selection will be performed forming groups of six transistors with similar electrical characteristics. Since the transistors have been derated in application to carry half-rated current, a current sharing ratio of two to one can be tolerated (neglecting temperature derating). If necessary, a simple series resistor can be introduced in the emitter circuit of the transistors, effecting base drive current as well as collector current sharing.

It should be noted that the saturation voltage drop of a transistor is a function of the transistor collector current. Hence, low saturation drop of even ordinary power transistors can be achieved to within limits by operating them at low currents. In part, this is the reason for operating the selected transistors at half rated current.

6.3.1.1.3 Redundancy Considerations

Since the flashlight reactor contains 108 TFE pairs, each of which represents a separate power source, it is assumed that no redundancy is required in the conversion equipment. A loss of one power converter channel represents a loss of less than 1 percent in the total power available from the reactor.

6.3.1.2 Flashlight Power System Integration

6.3.1.2.1 Reactor Integration

The main converter module detailed on Figure 6-2 is connected to the TFE pair through a limiter or fuse, the function of which is to open the circuit between the TFE pair and the converter in case of internal converter faults. The intention is to prevent physical damage within the converter because of high short circuit currents. It is recognized that operation of the fuse open circuits the TFE pair, and may cause overheating and failure of the TFE pairs. The alternative would be to provide some means of short circuiting the TFE's in the case of disconnection of the converter. Short circuiting means are not provided in the design because the condition of open-circuiting by converter failure is considered equivalent to open-circuiting of a TFE because of an internal fault. Consequently, there are no provisions against overheating for either a TFE failure or power conditioning failure. Future study should be performed to determine if a problem exists.

Diodes across each TFE are included within the converter to provide a path for the current from the surviving TFE in the event of open-circuit failure of the other.

An input filter consisting of a capacitor and reactor is included in the converter design to limit the voltage excursions at the input to the converter during those portions of the normal operating cycle when the converter transistors are off and the TFE pairs are unloaded. At a 10-kHz switching frequency for the converters connected to each TFE pair, the fluctuations in unfiltered TFE current represented by converters switching with pulse width modulation are not detrimental to the thermionic diodes. Diodes have long thermal time constants of several seconds at least, so the rapid switching will not affect instantaneous

temperatures. Filtering may not be necessary from the standpoint of the diodes; however, instantaneous changes in current between some large value and zero will cause instantaneous changes in diode output voltages as indicated by the typical diode characteristics shown in Figure 6-3.

During the intervals when current is zero, diode voltage will increase. Hence, from the standpoint of protection of the converters, input filtering is provided. In addition, the filter circuits provide nearly constant current flow in the low voltage leads from the thermionic reactor during the converter switching cycle, and effectively reduce the low voltage cable power loss.

6.3.1.2.2 Electrical System Control

Current transformers in the converters are included to provide signals representing TFE currents for system control load sharing, reactor control, and telemetry information.

During each of the three modes of operation (normal, one-half voltage with one TFE failed, and 10 percent power) the load sharing by the TFE's is controlled by pulse width modulation cycling of the individual converters. Control of the inverter conduction cycle relative to the non-conduction time is exercised by regulation circuits which sense the input current. Modifying functions to the control are the location of the TFE in the reactor, and whether the system is operating in the coast phase.

During normal and half-voltage operation, when the principal load is the thruster screens and the high voltage output is utilized, voltage regulation is exercised by regulating circuits which sense the high voltage at the load bus and control the reactor operation to maintain this voltage constant. The 250-volt output is separately regulated by phase controlling SCR's as the rectifiers in its output circuit.

During the coast period when 10 percent power is required, the thrusters are de-energized and there is no load on the 3100-volt bus. Reactor control is maintained by switching regulation to the 250-volt bus.

The third set of control circuits operates the contactor, which switches the main transistor groups from the normal to the 1/2-voltage taps. These control circuits sense voltage unbalance in the TFE pairs and operate the contactors if the voltages become unbalanced because of a fault in one of the TFE's.

In order that a common screen supply be feasible, several factors must be considered. If all screens are fed from a common supply, all are interconnected electrically. Hence, it is necessary that such interconnection be compatible with the complete electrical system, including the thruster auxiliary power conditioners. Also, it must be possible to isolate individual thrusters from the common supply in the event that the thrusters fail on momentary arc-over.

Each individual thruster screen is fed from the common high-voltage bus at the thrusters through a series network consisting of a high-speed electronic switch (SCR) and a series reactor (L). A simplified schematic diagram of the solid-state switch used as the screen circuit interrupter is shown in Figure 6-4. A number of SCR's are connected in series to withstand the high voltage of the screen supply and are connected in parallel with resistor-capacitor networks to provide for proper steady-state and transient voltage division. Commutation of the main SCR's is provided by firing the auxiliary SCR, connecting the charged capacitor across the main SCR's providing a momentary reverse bias, and shutting off the main SCR's.

The interrupters operate immediately upon the development of a fault. The series inductors provide the energy necessary to clear the fault, as well as providing momentary, transient circuit isolation during faults.

The main SCR interrupts the circuit between screen and the power bus in the event of an arc within the thrusters, as detected by a sudden drop in voltage at the screen, the appearance of voltage across the series reactor, L, or a commanded signal. Following circuit interruption by the SCR, energy stored in the inductor, L, continues to supply power to the arc for a period of up to two milliseconds. The SCR remains off for a period of 0.2

seconds to allow time for the arc to clear and the thruster conditions to return to normal. After 0.2 second, the SCR is switched on again, reestablishing screen voltage and hopefully restoring full thruster operation. If the arc restrikes three times within ten seconds, the screen supply to that thruster and the inputs to the auxiliary power suppl ies for that thruster are permanently disconnected. This thruster is considered disabled and one of the six spare thrusters is placed into operation.

During the spacecraft coast period when the thrusters are not required to operate, power to the thrusters is disconnected by the static switches in the screen supplies and by the contactors in the input circuits to the auxiliary thruster power supplies.

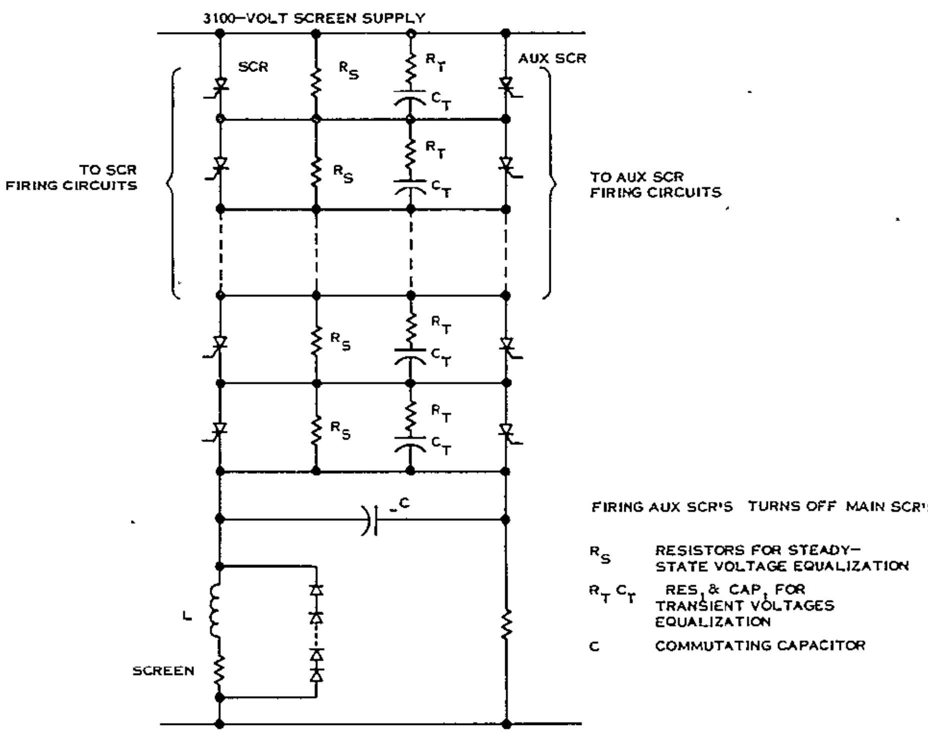

Figure 6-4. Screen Circuit Interrupter

6.3.1.3 Main Converter Mechanical Design

6.3.1.3.1 Geometry

Components of the main power conditioner are mounted using a baseplate integral to the radiator. Figure 6-5, layout drawing, and Figure 6-6, isometric drawing, show the components configured within a 1 square-foot area. The suggested layout is designed to accept power at one side and have the outputs on the opposite side, thus simplifying the component construction, testing, and integration.

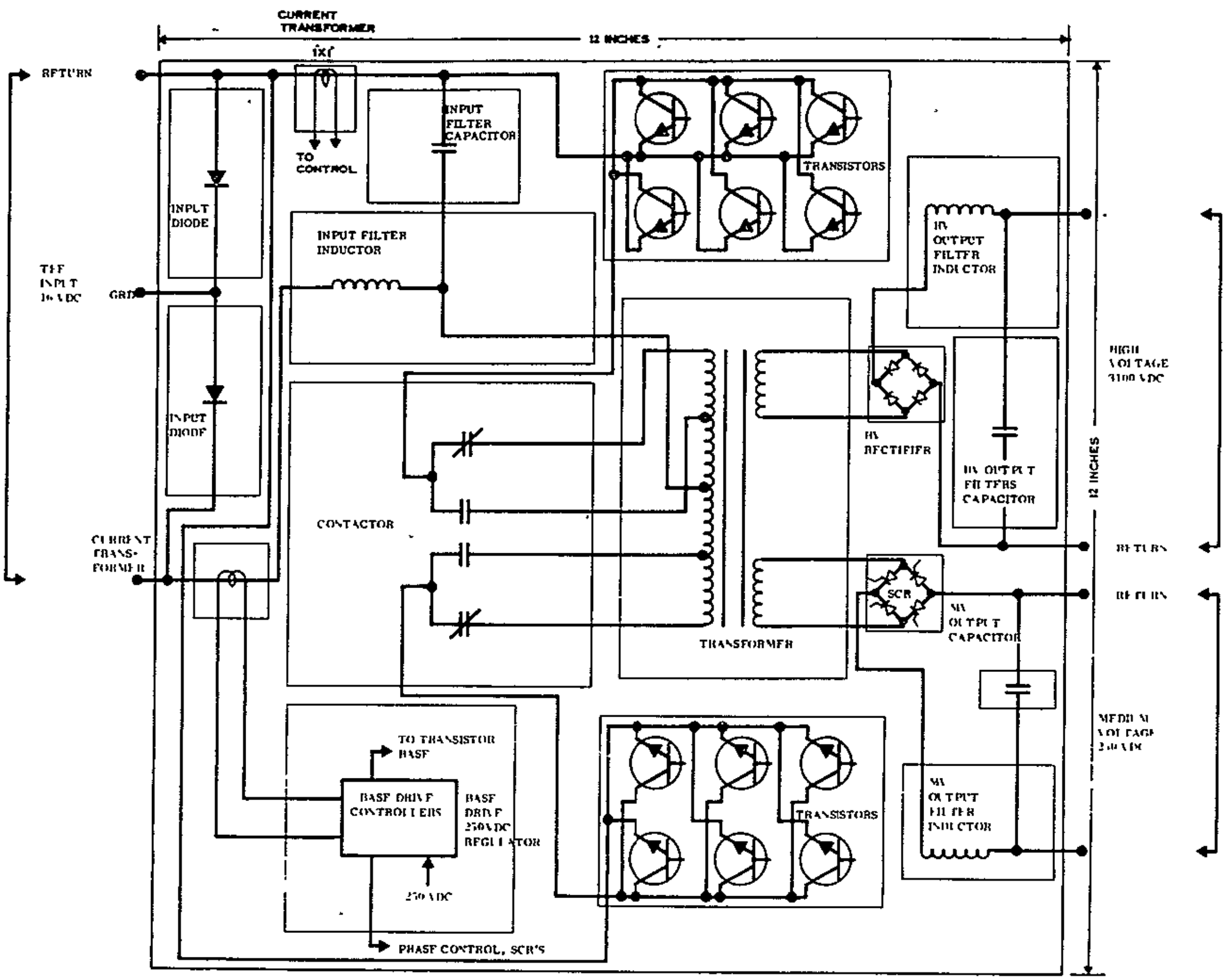

Figure 6-5. Component Geometry Main Power Converters Flashlight Reactor System

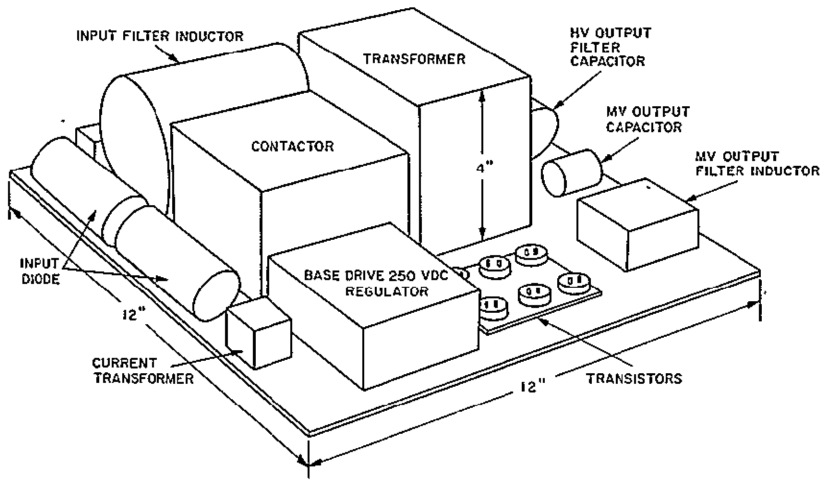

Figure 6-6. Reactor Power Regulation Arrangement Nominal 3 kWe Module Flashlight Reactor System

6.3.1.3.2 Component Size

The following components have been selected for use in the main power conditioners. Weights for each device are shown in Table 6-4.

a. Input Filter

Inductor:	2.0 x 4.0 inches diameter 5 h 7 turns, 5 cm length, 10 cm diameter AWG number 4, copper wire
Capacitor:	1.3 x 2.5 x 3.0 inches H 4 - GE-KSR Tantalum Foil 200 μf, 100v, type 29F3265

b. Bypass Rectifiers: 2.5 x 1.2 inches diameter
200a, 200v
Type GE-1N3264

c. Inverter

Transformer:	5.0 x 3.0 x 4.0 inches H Electrical steel, Hymu-80 Input: 14 to 18 vdc, 196.9a maximum Outputs: 3100 vdc, 2.3a 250 vdc, 1.7a Tapped Primary
Transistors:	Mounted on two panels bonded to radiator Six transistors/heat sink Transistor type: Westinghouse 1776-1460 0.5 x 0.9 inches diameter 60 a, 140v

d. HV Output Rectifiers:	Bonded block, 1.0 x 1.0 x 0.5 inches H 12 diodes/block, 3 diodes/branch Diodes: 3a 800v Type: GE-A15N 0.15 x 0.2 inches diameter Axial lead

e. HV Filter

Inductor	2.25 x 1.8 x 1.8 inches H 8 cubic inches
Capacitor:	3.8 x 1.6 inches diameter Axial
f. MV Output Rectifiers:	0.4 x 0.3 x 0.6 inches H 3-Silicon controlled rectifiers Stacked flat pack SCR: Similar to Type GE-C106 0.4 x 0.3 x 0.2 inches H

g. MV Filter

Inductor:	2.0 x 1.5 x 1.0 inches H
Capacitor:	1.0 x 3.6 in. diameter Tubular tantalum foil
h. Contactor:	4.0 x 4.0 x 3.0 inches H 250a, 120vdc, DPDT, latching

i.	Control Circuits: (Base drive, SCR Phasing)	3.0 x 3.0 x 1.5 inches H 5 control boards 2 power transistors, similar to 1776-1460
j.	Current Transformer:	1.0 x 1.0 x 1.0 inches H 2 toroids and power supply

6.3.1.4 Influence of Reactor Output Voltage

One means of increasing power conditioner efficiency that is within the state of the art is by increasing reactor output voltage. In addition, low voltage cable losses and weights are affected, as well as the system configuration, if the voltage can become high enough. It is recognized that there are many issues to be resolved, including:

a. Reactor reliability against open-circuit failure

b. Sheath arcing question at high collector potentials

c. Mechanical and thermal/hydraulic design of a U-tube internal reactor electrical hookup

d. TFE lifetime

This paragraph examines the sensitivity of the powerplant design to output voltage to determine whether the potential savings warrant consideration of a more complex TFE electrical arrangement approach.

The effect of reactor output voltage on power conditioner module efficiency and weight is estimated in Figure 6-7. For greater than 60 volts, an alternate design concept, using Silicon Controlled Rectifier (SCR) switching, is employed. This information, together with reoptimization of low voltage leads, yields the specific weight savings data of Figure 6-8. At voltages above 50 volts, it is possible to provide even greater weight savings by relocating the power conditioner equipment to the far end of the plant, thus saving more on shield and radiator feed line weight than is lost in cable losses, as is also shown on Figure 6-8. These computations are preliminary and do not take secondary effects, such

as a change in reactor efficiency for some methods of increasing voltage, into account. As may be noted, at about 40 volts, most of the potential gain is realized, and at about 50 volts, the savings are independent of configuration selection.

6.3.1.5 Auxiliary Power Conditioning

DC conduction electromagnetic pumps are selected for use with the thermionic reactor system. These pumps require very high current at very low voltage, specifically for the primary pump, 5000 amperes at 0.5 to 1.0 volts. Special additional power conditioning equipment, therefore, is necessary. Using conventional power conversion schemes for very low voltage, efficiencies of less than 50 percent are encountered. With dc-ac-dc conversion, the voltage drop in the output rectifiers approximates or exceeds the output voltage required and hence the efficiency is poor.

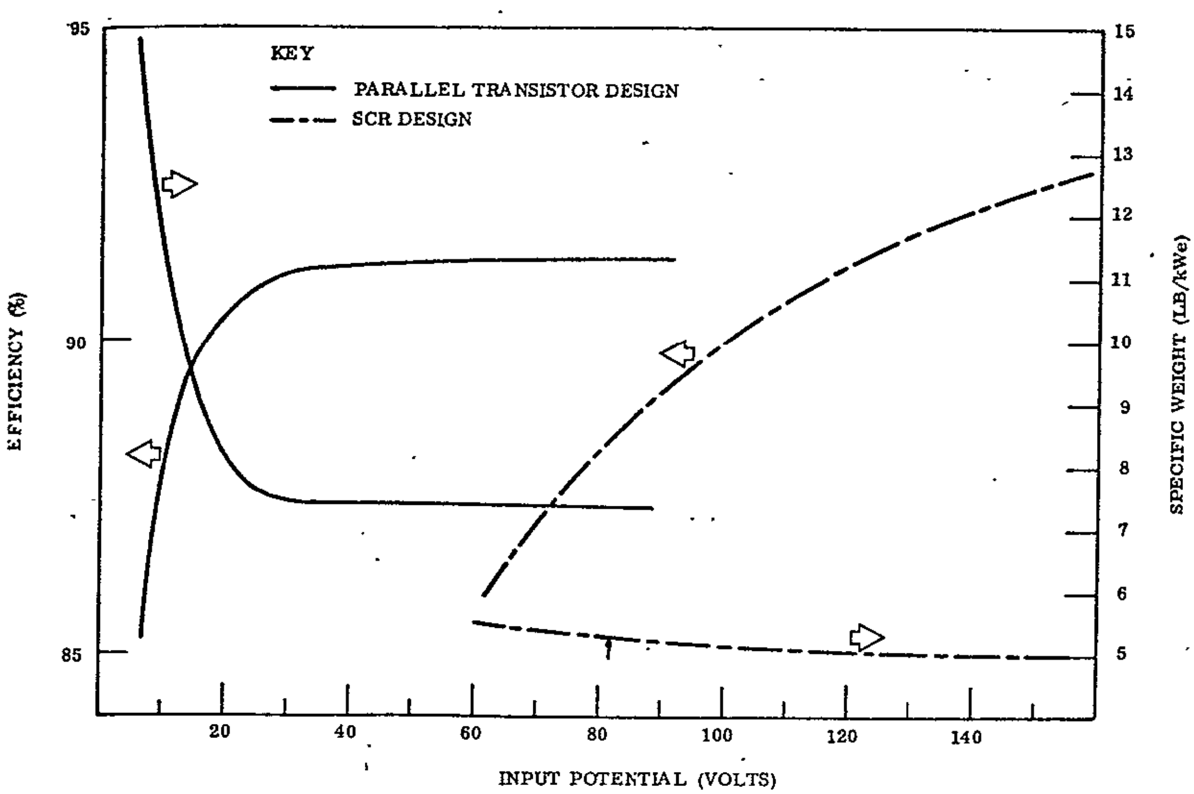

Figure 6-7. Parametric Characteristics of the Main Power Conditioner

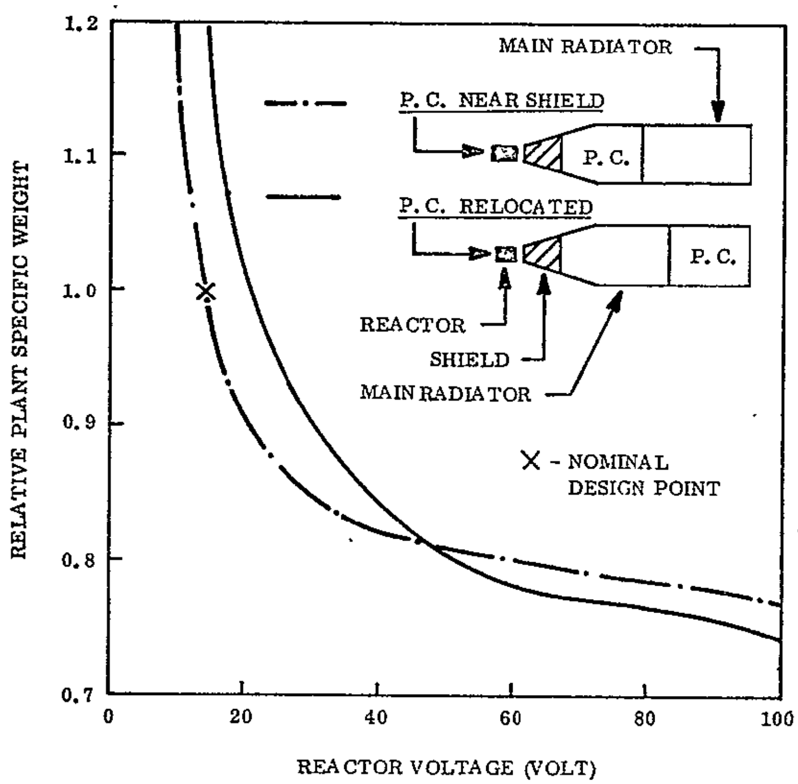

Figure 6-8. Effect of Reactor Voltage on Specific Weight

In order to obtain the extremely low dc output voltage required at the pumps, standard low-voltage conversion to a higher output voltage is performed and several pumps are connected in series. With an output potential of 10 volts dc, an efficiency of approximately 85 percent is realizable. A standard 8 pounds/kWe has been applied for weight estimation for the main EM pump power conditioner.

6.3.2 EXTERNALLY FUELED THERMIONIC REACTOR POWER SYSTEM DESIGN

The electrical power system developed for the externally fueled thermionic reactor (EFTR) is shown in Figure 6-9.

The following discussion is concerned with the main power conditioner design, since the baseline for the rest of the system is unchanged from the flashlight design insofar as techniques and specific weights are concerned.

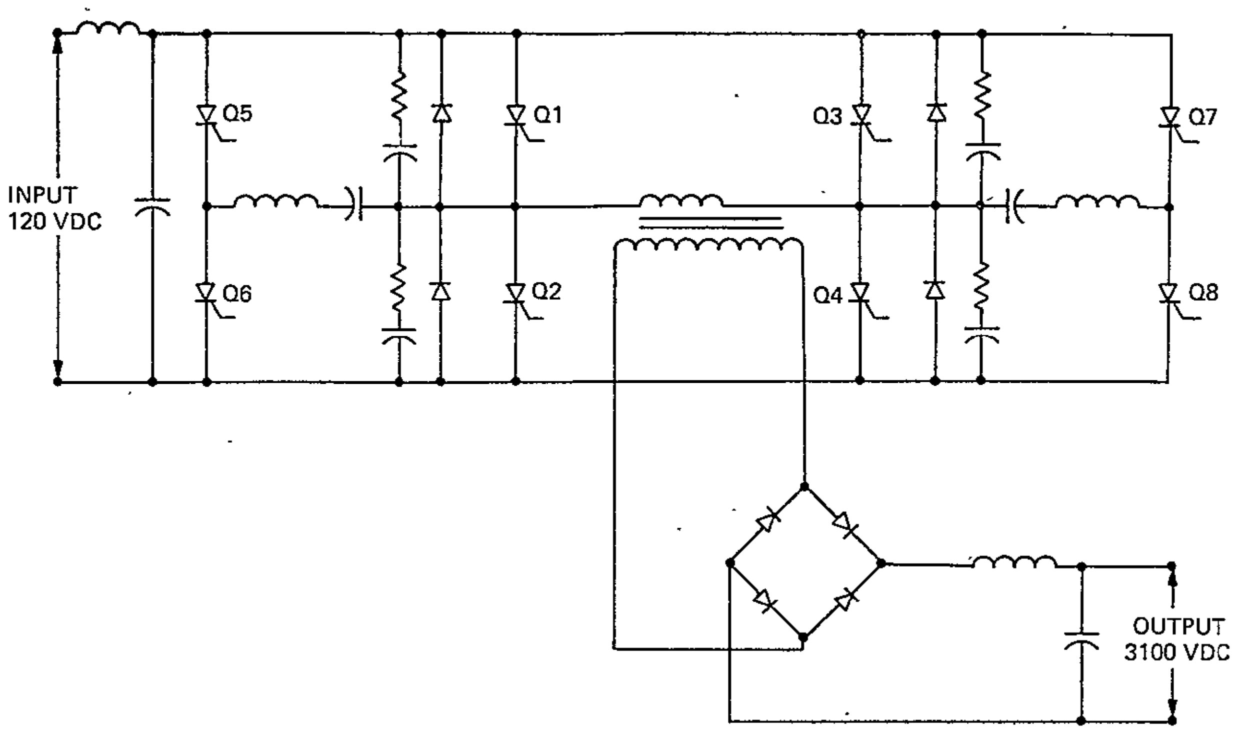

Figure 6-9. Main Power Conditioner Externally Fueled Thermionic Reactor System

Electrical power output from the generator is sufficiently high so as to be an integral part of the medium voltage distribution bus. Power comes from a single output at a potential of 120 volts, and is distributed directly to the auxiliary loads, as well as the main power conditioners without being transformed. The main power conditioners convert the 120-volt input to 3100 volts for the screen electrodes of the ion thrusters. With individual power conditioners for each engine, no separate screen circuit interrupters are necessary. Screen circuit current limiting and thruster turn-off will occur in the affected power conditioner.

System weights and losses are shown in Tables 6-6 and 6-7, respectively.

Baseline component weight for the EFTR power conditioner is presented in Table 6-8.

The electrical schematic of the main power conditioner is shown on Figure 6-10. Figure 6-11 shows the parametric characteristics of the EFR main power conditioner as a function of input voltage.

TABLE 6-6. ELECTRICAL SYSTEM WEIGHT SUMMARY EXTERNALLY FUELED REACTOR SYSTEM

Component	Weight (lb)
Main Conditioners	1314
Power Distribution Cables	275
Screen Supply Interrupters	----
Auxiliary Power Conditioners	507
Totals	2096
Specific Weight (Load, 297.4 kW)	7.0 lb/kWe

Electrical system design for the externally fueled reactor system is based upon each ion-thruster being driven by a separate power conditioner. There are 37 thrusters/power conditioner groups on the spacecraft, 6 of which are spares to be used following a failure of one of the initially active engines.

One of the control loops of the reactor senses the reactor output voltage, and regulates incremental changes in heat generation to maintain a constant output voltage. Therefore, under normal conditions, regardless of load, the input potential to the power conditioners is 120 volts dc. Allowing for an input voltage to vary over a range due to other than normal reactor operation, the power conditioners are designed to perform with an input voltage of 90 to 130 volts, direct current.

TABLE 6-7. EXTERNALLY-FUELED REACTOR ELECTRICAL SYSTEM POWER BALANCE

Losses	Watts
Main Power Conditioners	
Main SCR's	464
Auxiliary SCR's	96
Transformers	216
Commutating Circuit (inductor/capacitor)	2
Feedback Diodes	8
Rectifier Diodes	7
Output Filter	45
Snubber Circuit (RC Filter)	4
Input Filter	22
Control Circuit	15
Total Losses, Single Power Conditioner	879
Total Main Power Conditioning Losses, 31 units	27,249
Screen Supply Interrupter	Not required
EM Pump Power Conditioning	3,700
Thruster Auxiliary PC*	*
Payload Power Conditioning	100
Reactor, Powerplant and Spacecraft Controls	322
Transmission Cables	6,420
Total Losses	34,091
Loads	**Watts**
Thruster Screen	223,000
Thruster Auxiliary Power	15,500
Payloads, Science	1,000
Guidance	500
System Control	500
Primary EM Pump	10,000
Secondary EM Pump	10,000
Shield Pump	100
Auxiliary Pump	100
Propellant Pump	100
Reactor Control	2,000
Cesium Heater	500
Total Loads	263,300
Total Power Required	297,391
Electrical System Efficiency	88.5%
Power Conditioning Efficiency	91.0%

*Losses are included in Ion Engine Efficiency

TABLE 6-8. EXTERNALLY FUELED REACTOR MAIN POWER CONDITIONER WEIGHT

Component	Weight, lbs.
Transformer	17.20
Main SCR's	1.25
Commutating SCR's	0.10
Commutating Circuit	
Capacitor	1.66
Inductor	0.04
Feedback Diodes	0.12
Rectifier Diodes	0.13
Output Filter	
Capacitor	1.06
Inductor	0.10
Snubber Circuit	
Capacitor	0.04
Resistor	0.04
Input Filter	
Capacitor	1.60
Inductor	1.90
Control Circuit	0.30
Miscellaneous Piece Parts (Wire, Mounting Brackets, Heatsines, etc.)	10.96
Individual Converter Weight	36.50
Total Weight, Main Power Conditioners, Externally Fueled Reactor System	1314.00
Power Converter Specific Weight (7.2 kWe)	5.1 lb/kWe

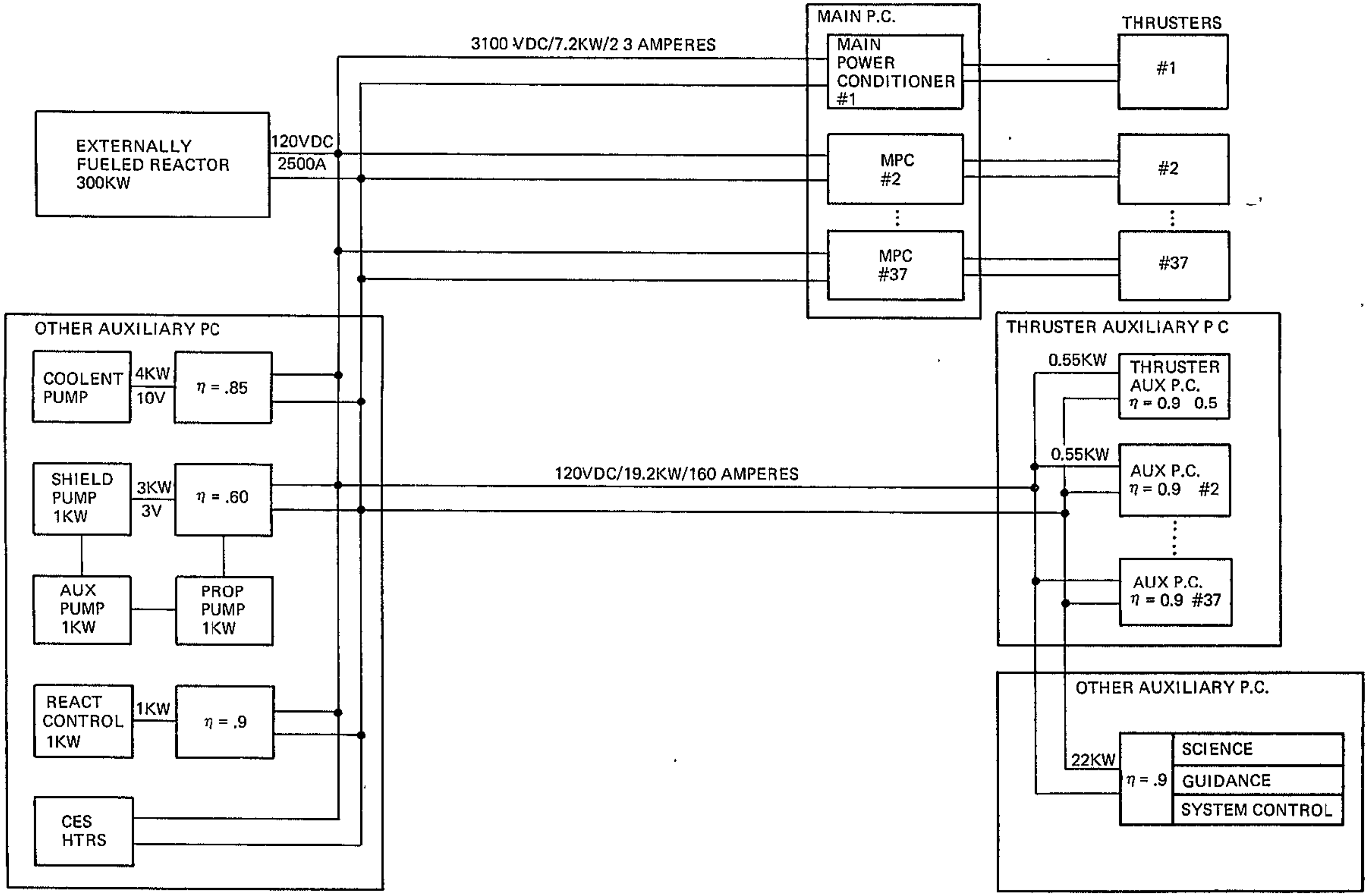

Figure 6-10. Externally Fueled Reactor Electrical Power System

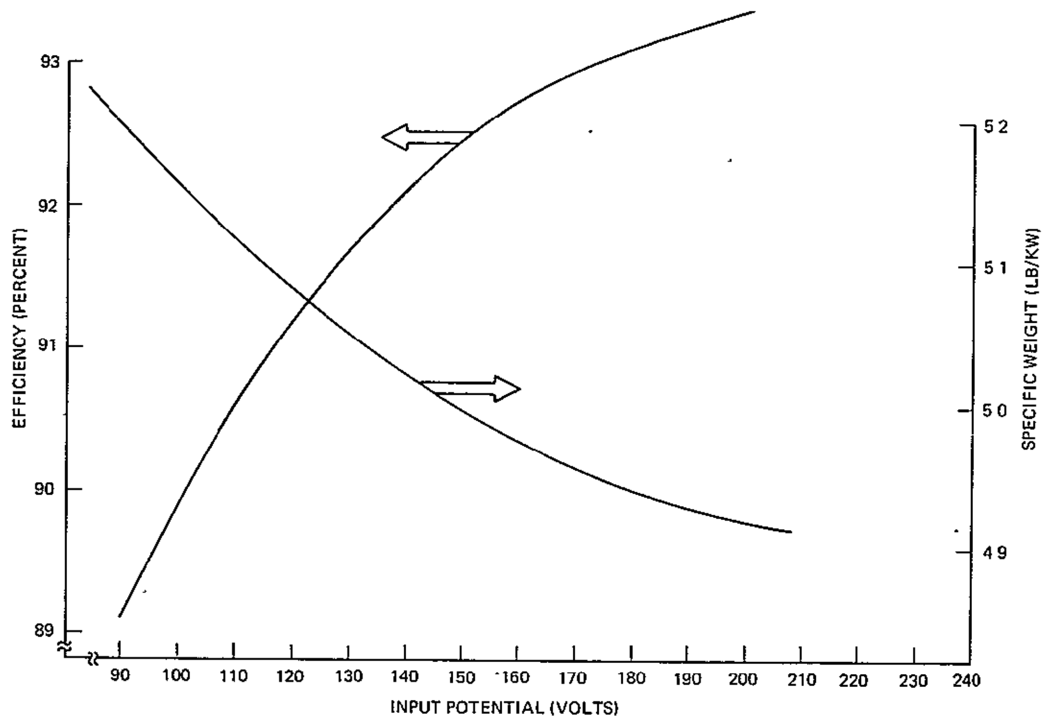

Figure 6-11. Parametric Characteristics of Main Power Conditioner Externally Fueled Reactor

A power conditioner circuit is required which is capable of converting 7.2 kW from the nominal 120 volts input potential to the 3100 volts required by the ion thrusters. This would result in switching 60 amperes in each main power conditioner. Numerous circuits could be used, but considering normal transistor V_{CE} limitations, and silicon controlled rectifier (SCR) commutation problems, the driven bridge circuit appears as the logical preference.

Included in the power conditioners is the capability to current limit the output and to shut down completely for arc extinguishing. During the 10 percent operation phase, which is during coast without engine thrust, the power conditioners will be shut down.

Electrical characteristics for the design of the main power conditioners to be used with the EFR system are as follows:

Input Voltage:	90 to 130 vdc, 120 vdc nominal
Input Current:	60 amperes
Output Voltage:	3100 vdc, 1% regulation
Current Limited:	125% overload

6.3.2.1 Inverter Design

The basic inversion function for the EFTR main power conditioner was selected to be performed by a bridge circuit, using SCR impulse commutation.

Inverter circuits are typically arranged in either a parallel (push-pull) or bridge configuration with transistors or Silicon Controlled Rectifier (SCR) switching elements. A bridge circuit has an advantage of operation up to twice the input voltage level limit of a parallel circuit due to the inherent auto-transformer action of the parallel circuit upon the switching device. With a 120-volt input potential, the effect upon transistors in a parallel circuit is to exceed the V_{CE} level of most high-current devices. SCR's used in a parallel circuit have commutation difficulty in the presence of pulse width modulation and variable load. Consequently the bridge circuit was selected.

6.3.2.2 Redundancy Considerations

The electrical design for the externally fueled thermionic reactor system is based upon a single thruster being driven by one power conditioner. Thirty-seven thrusters and conditioners are on board , of which six are spares. Although this provides some power conditioning redundancy, the use of 37 ion engine-PC modules provides for ion engine isolation.

6.3.2.3 Main Coverter Mechanical Design

6.3.2.3.1 Geometry

As with the power conditioners for the flashlight reactor, the components will be mounted using the baseplate as part of the radiator. Figure 6-12 shows the components configured in a minimum area design of approximately two square feet. Additional area may be required for thermal dissipation.

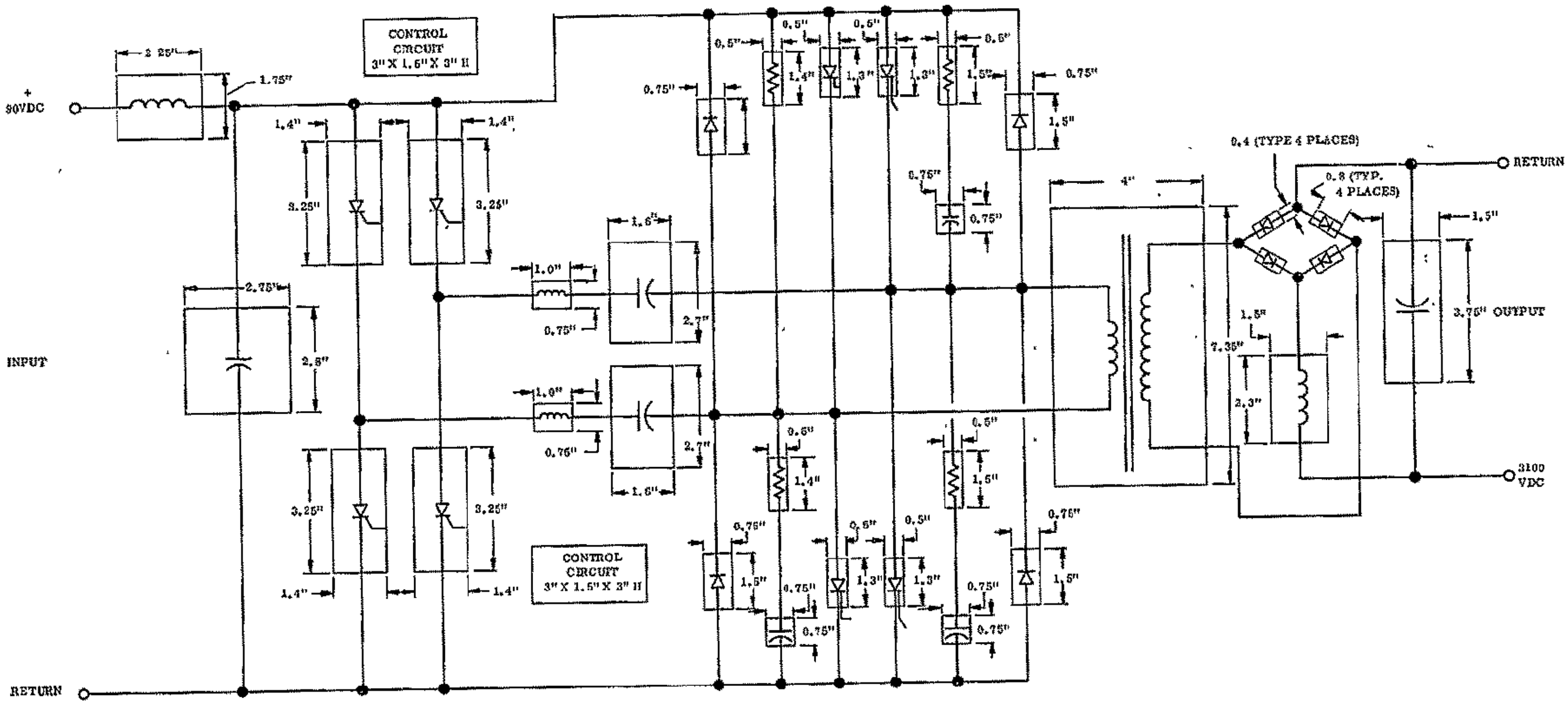

Figure 6-12. Component Geometry, Externally Fueled Reactor Main Power Conditioner

6.3.2.3.2 Component Size

The following components have been selected for use in the main power conditioner for the externally fueled reactor system.

a. Input Filter

Inductor:	2.25 x 1.6 x 4.12 inches 16 turns No. 6 gauge wire AL-19 Silectron Core Arnold Engineering Company
Capacitors:	6, each 1.3 x 0.75 x 2.5 inches H GEKSR Tantalum Foil 100 μfd, 100 v

b. Main SCR's, 4:	3.25 x 1.4 inches diameter GE type C185 600 v, 235 Amps
c. Transformer:	8KLDe, 2kHz 7.35 x 4 x 7 inches H
d. Feedback Diodes, 4:	1.5 x 0.75 inches diameter GE type IN248 14 ampere

e. RC Snubber

Capacitor, 4:	0.75 x 0.25 inches diameter GE type 151EC, 61F19BA223 Lectrofilm-B Tubular 0.02 f, 180v
Resistor, 4:	1.4 x 0.5 inches diameter 20 ohm, 10 watt

f. Commutating Circuit

Inductor, 2:	0.6 x 1 inch diameter Magnetics Inc. 125 Permeability Powdered Permalloy 10 turns, No. 13 gauge, bifiler

Capacitor, 2:	2.7 x 1.6 x 4.5 inches H GE Type 160EC SCR Commutating Capacitor 200 pkv, 20 μfd
g. Auxiliary, SCR's, 4:	1.3 x 0.5 inches diameter GE Type C35 35 ampere, rms
h. Output Filter	
Inductor:	1.5 x 2.3 inches diameter Magnetics Inc. 55086 Powder Permalloy 333 turns, No. 16 guage wire 32 mh
Capacitor:	3.75 x 1.5 x 4 inches H GE Type 23F1132 Paper/Pyranol 5000 vdc, 1600 ac, 0.5 μfd
i. Rectifier Diodes, 8:	Block 4 diodes, 1 x 1 x 1 inch H Each diode, IN1616R 0.8 x 0.4 inch Diameter 5 amperes, 600 prv
j. Control Circuit, 2:	3 x 1.5 x 3 inches H Flatpack, Board Construction

6.4 DYNAMIC ELECTRIC POWER CONVERSION

Dynamic electric power conversion is one in which power conversion is performed by use of a motor-generator (M-G) set. Application of a dynamic approach is considered for large space power systems, since a rotating generator is one of the most efficient and lightest weight energy electrical converters. A generator with an efficiency of about 94 percent with specific weight of less than 1 lb/kWe was selected for the Thermionic Spacecraft Application, resulting in a system with efficiency of 93 percent and a specific weight of 7.2 lb/kWe, not including radiator weight savings.

The dynamic electrical system for the 300-kWe electrical propulsion spacecraft with a flashlight thermionic reactor power source consists of a motor-generator set, transformers, and rectifiers. The power system schematic is shown in Figure 6-13. The estimated power loss and weight breakdowns for the principle components are shown in Tables 6-9 and 6-10 respectively.

Electrical power from the thermionic reactor at low voltage and high current is delivered to an acyclic motor which is coupled directly to a homopolar inductor-type alternator. The alternator develops an output of 250 volts, three phase, 2 kHz ac, which is fed to two types of loads. Part of the 250-volt ac output is rectified and supplies the 250-volt dc hotel bus. The remaining 250-volt ac power, which is approximately 80 percent of the system electrical capacity, is transformed to 3100 vac, and full wave rectified to form the 3100 vdc thruster screen bus.

One of the most efficient dc machines operating from, or generating, low voltage and high currents is the acyclic machine. A simplied form is shown in Figure 6-14. An acyclic motor consists of a conducting drum rotating in a dc magnetic field produced by the exciting coils. The voltage impressed on the conducting drum is applied through the sliding brushes on the drum creating a repelling force against the field, causing the shaft to rotate. According to Faraday's Law, the angular velocity of the machine is proportional to the total flux and the voltage supplied to the drum. Consequently, the motor shaft speed can be effected by changing these parameters, which can change the resulting generator output (Reference 8).

Conventional sliding brushes on the drum have the undesirable features of high friction losses and high brush contact voltage drop and in a space application have the additional problem of brush particle accumulation. The acyclic machines employ a liquid-metal collecting system instead of sliding brushes, minimizing these problems. An alloy of sodium and potassium (NaK) effectively connects the current carrying parts of the rotor and stator.

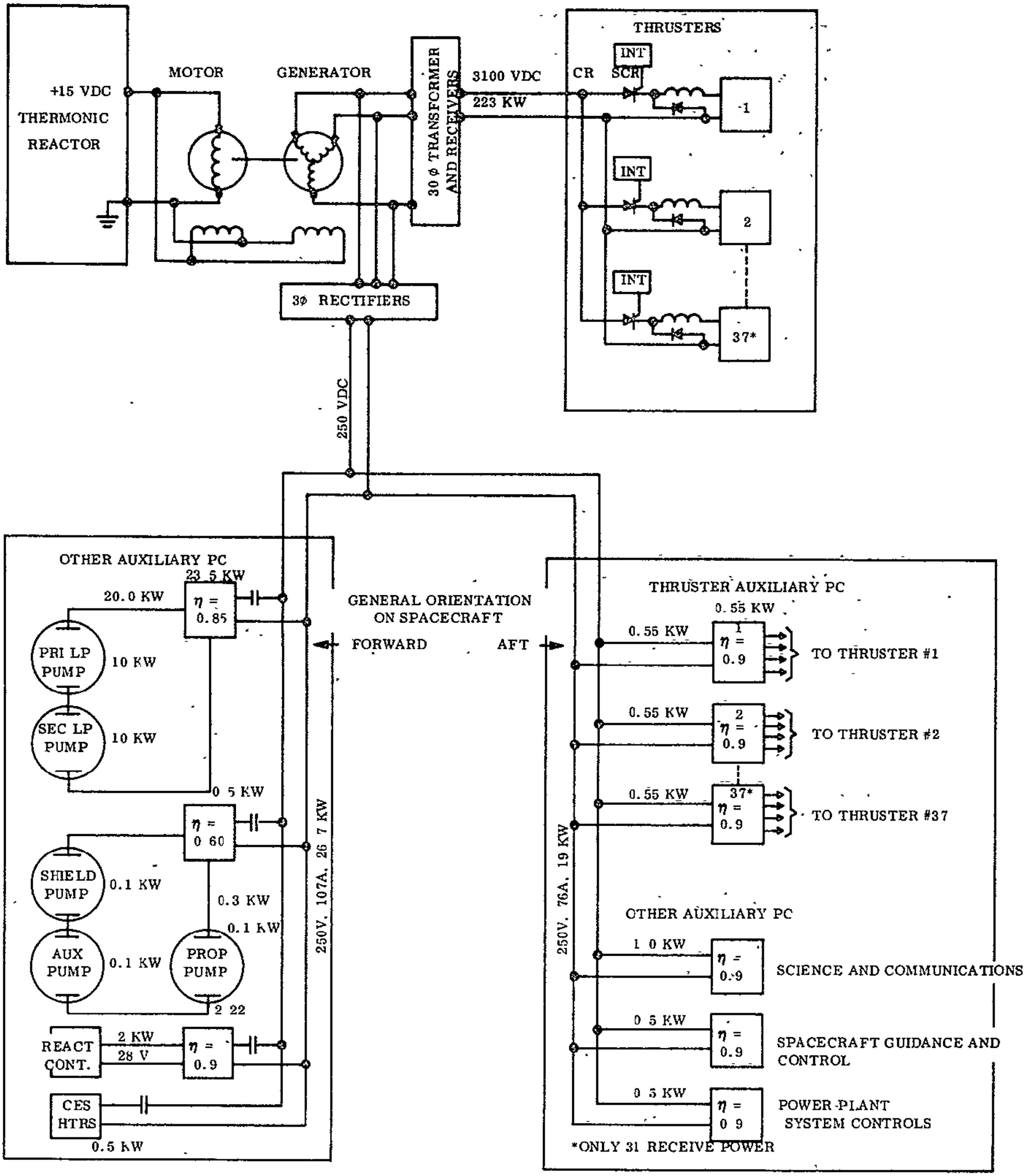

Figure 6-13. Dynamic Electrical System Power System Schematic

TABLE 6-9. ACYCLIC ALTERNATOR SYSTEM POWER BALANCE

LOSSES	WATTS
Motor (η = 97%)	900
Generator (η = 94%)	1,800
Transformer	885
Rectifiers	
High Voltage	528
Low Voltage	220
Transmission Cables	
Motor	9,600
High Voltage	120
Low Voltage	190
Screen Interrupters	1,250
Thruster Auxiliary Power Conditioner	*
EM Pump Power Conditioners	3,700
Payload Power Conditioner	100
Reactor Powerplant and Spacecraft Controls	322
Total Losses	19,615
LOADS	**WATTS**
Thruster Screen	223,000
Thruster Auxiliary Power	17,000
Payloads, Science	1,000
Guidance	500
System Control	500
Primary EM Pump	10,000
Secondary EM Pump	10,000
Shield Pump	100
Auxiliary Pump	100
Propellant Pump	100
Reactor Control	2,000
Cesium Heater	500
Total Loads	264,800
Total Power Required	284,415
Efficiency	93.1%

*Losses included in Ion Engine Efficiency

TABLE 6-10. ACYCLIC ALTERNATOR SYSTEM, ELECTRICAL SYSTEM WEIGHT

Component	Weight (Pounds)
Motor	250
Generator	250
Transformer	180
Screen Supply Interruptions	310
Thruster Auxiliary Power Conditioners	272
EM Pump Power Conditioners	55
Payload Power Conditioners	30
Reactor, Powerplant and Spacecraft Control	15
Transmission Cables	490
Rectifiers	10
Wire, Brackets, Heat Paths, Control Logic	180
Gas System, Bearings	25
Total Weight	2067 Pounds
Specific Weight (Load, 284.4 kWe)	7.2 lb/kWe

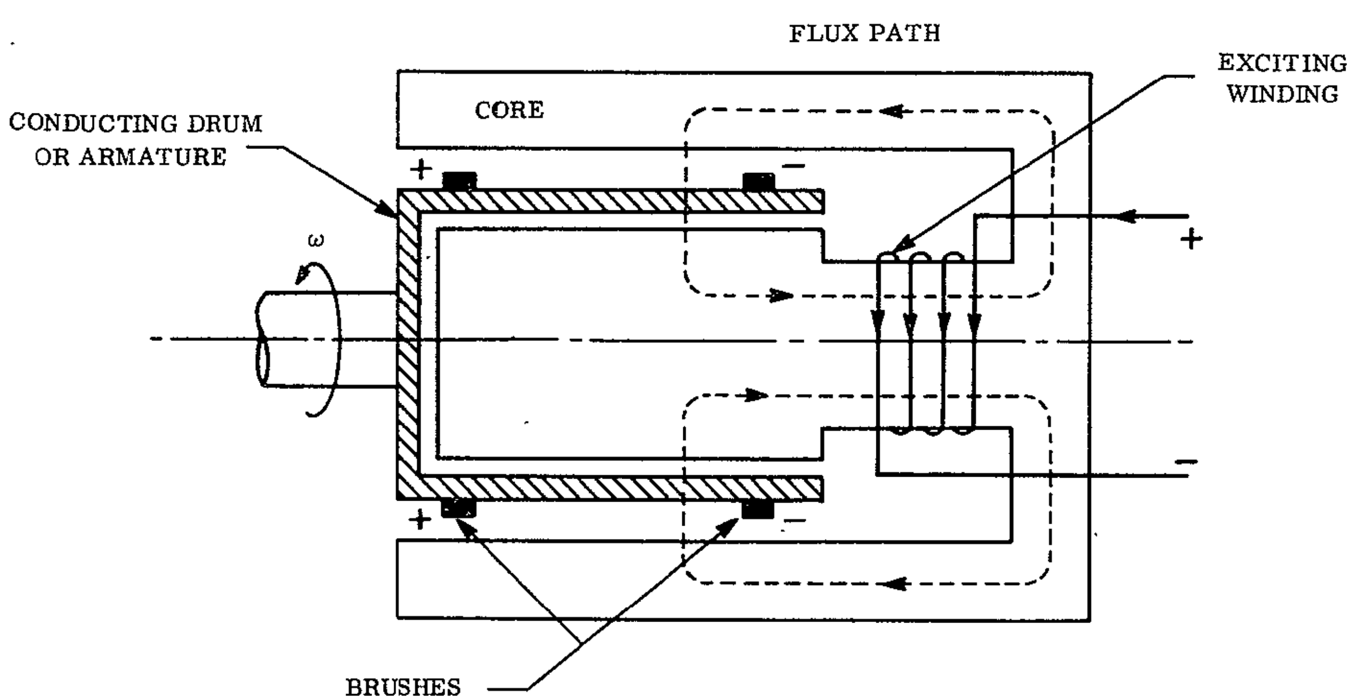

Figure 6-14. Simplified Acyclic Motor

The generator is a homopolar inductor type of synchronous alternator. This machine has a solid unwound rotor, losses of which can be made low under these balanced load conditions. Furthermore, inductor alternator specific weight is sensitive to load power factor; however, with these types of loads, power factor is greater than 0.8 and the effect is minimal.

Both the motor and generator have gas bearings and operate in a low pressure argon or xenon environment.

The acyclic motor has a solid rotor of 43:40 magnetic steel with inconel on the surface of the rotor to minimize windage losses. Stator punchings are of low carbon steel of thin lamination for reducing eddy currents. Windings are of copper. The homopolar inductor generator is similarly constructed.

The M-G set, operating at 60,000 rpm, with a coolant temperature of 300°F, weighs about 250 lb for each unit. The alternator having four poles has an output of 2000 Hertz. Each unit has a volume of approximately 10 inches diameter by 12 inches long.

Excitation for both units of the M-G set is provided directly from the low voltage thermionic reactor. Excitation power required is about 0.1 percent of the output rating of the units compared to 0.5 percent to 1.0 percent for commutator type generators.

Reliability may be obtained through use of four independent motor-generator sets operating in parallel. Each set may be provided with 33 percent reserve capacity, so that full power can be maintained after failure of one set. Only very small weight penalties are involved because of the inherent high efficiency and low specific weights of the dynamic systems. Non-redundant system weights are shown in the weight tables for comparison with other methods of conversion. Further study is required to fully assess the relative tradeoffs associated with the dynamic power conditioning approach.

It is fully recognized that the inherent static power conversion system characteristics of the thermionic approach cannot be fully utilized if dynamic power conditioning is employed.

This cursory evaluation indicates that further investigation is required to assess the relative reliability aspects of the two approaches. Emphasis should be placed upon the definition of the relative reliability of these candidate static and dynamic power conditioning approaches. The scope of this effort should include reactor reliability and examination of smaller redundant units.

7. SPACECRAFT DESIGN DEFINITION

7. SPACECRAFT DESIGN DEFINITION

This section of the report describes the reference designs for the externally fueled reactor spacecraft and the flashlight reactor spacecraft shown in layout in Figures 1-1 and 1-5, respectively. Each reference design has a net propulsion power of 240 kWe with a reactor output power of 274 kWe for the externally fueled reactor and a reactor output power of 318 kWe for the flashlight reactor.

These designs are based on the results of a thermionic spacecraft weight optimization computer code, which is reported separately (Reference 7).

7.1 EXTERNALLY FUELED POWERPLANT/SPACECRAFT

An externally fueled reactor powered spacecraft was designed and optimized with a computer code analysis based on the design guidelines presented in Section 3, and the following additional conditions:

a. A single heat rejection loop between reactor and main radiator.

b. A radiator arrangement with the main radiator directly behind the shield and the power conditioning radiator at the rear of the spacecraft.

c. Aluminum as the electric cable material.

As detailed in Section 1.2, the total net power of 240 kWe is the sum of the ion engine input and the special ion engine PC input power. Details of the powerplant hotel load and the payload plus ion engine PC section load are given in Table 1-3.

A layout drawing of the reference externally fueled reactor spacecraft is given in Figure 1-1. The vehicle is a long cylinder with the forward one-third section conical in configuration. The overall length is 62.7 feet with the conical section 29.3 feet long and the diameter is 9.2 feet. The conical section has a shield half angle of 6.6 degrees.

The reactor end of the vehicle, is designated the forward end since the spacecraft is propelled in that direction on a line coincident with the longitudinal axis of the vehicle by the ion engine thrusters at the rear end. The reactor is so located to provide maximum separation from the payload in the rear section of the vehicle and to assure minimum volume and weight for the shadow shield. The shield is formed in two sections; a solid block of neutron shielding directly behind the reactor, followed by a tank of mercury propellant which functions as the gamma shield.

The main heat rejection radiator, which dissipates the waste thermal energy generated by the reactor, forms the conical section of the spacecraft behind the shield with an additional bay extending down the cylindrical section. A single piping loop transports the NaK reactor coolant around the shield to the main radiator feed line network. The coolant activation analysis indicates that use of a single primary coolant loop in the externally fueled reactor powered spacecraft does not violate the integrated gamma dose limit of 10^7 rads.

A very short section of auxiliary radiator separates the main radiator from the power conditioning radiator, which occupies most of the cylindrical section of the vehicle. The PC radiator is actually eight-sided in cross section, rather than cylindrical, and separated axially into two halves by two narrow strips along which the low voltage cables are strung. The low voltage cables attach to the reactor leads at the rear of the reactor, then run longitudinally along the surface of the shield and main radiator to the PC radiator distribution area. At 5 axial locations on the PC radiator, low voltage cables are strung circumferentially to 38 individual power conditioning modules spotted uniformly on the flat panel sides of the PC radiator.

The rear 4.8 feet of the spacecraft contain the payload and ion engine subsystems. Communication antennas which extend radially for operation are shown in the stowed position behind the thrusters for launch.

Summary descriptions of the spacecraft subsystems are presented in the following paragraphs. Further details may be found in Reference 3.

The propulsion system is the major system of interest in this report. It consists of two subsystem groups, the powerplant subsystem group and the thrust subsystem group. To simplify the numerical designations of the paragraph headings and subheadings in this report section, the two subsystem groups mentioned above will be given equal importance in numerical designation with the spacecraft propellant system and payload system.

7.1.1 POWERPLANT SUBSYSTEM GROUP

The Powerplant Subsystem Group consists of the reactor subsystem, the shield, the primary and auxiliary heat rejection subsystems, the electrical and control subsystem, and powerplant structure.

The 274 kWe externally-fueled reactor is 2.75 feet in diameter and 1.68 feet long. In the dry condition, it weighs 4150 pounds and holds 75 pounds of NaK when filled for operation. Twelve SNAP-8 type control actuators are mounted on the front face of the reactor to drive the control drums in the radial reflector. The control actuators are modified with the output drive eccentric to the motor shafts. This allows grouping the actuators closer to the axial centerline of the reactor thus reducing the radial diameter of the shadow shield. The actuators are radiatively cooled and unprotected from the reactor nuclear radiation. The weight of the twelve actuators is 230 pounds.

7.1.1.1 Shield Subsystem

The shield subsystem consists of a canned block of lithium hydride and plugs of tungsten metal which shield the holes across the outer circumference of the propellant tank caused by the passage of the reactor loop piping. The lithium hydride block performs most of the

required neutron shielding with additional neutron attenuation occurring in the conically shaped mercury propellant tank placed directly behind the neutron shield. The primary reason for this mercury tank location is that it permits the mercury propellant to act as the primary gamma shield for the radiation sensitive components of the spacecraft.

The neutron shield component is an internally supported can filled with lithium hydride. The can is 16 inches thick and has an average diameter of 41.8 inches. It weighs 765 pounds of which 575 pounds is lithium hydride.

The total heating rate in the shield subsystem is estimated to 1.3 kW, with almost all of this heat being deposited in the frontal region of the neutron shield. Cooling is achieved by a serpentine coil of pipe carrying the auxiliary cooling system coolant.

7.1.1.2 Primary Heat Rejection Subsystem

The primary heat rejection is composed of the main radiator and the piping network which pumps and transports the reactor coolant to the radiator. The radiator consists of four approximately equal length bays, three of which form the conical surface of the spaacecraft while the fourth occupies the forward section of the cylindrical spacecraft area. Each of the bays is divided into three panels, each of which cover a 120-degree section of the bay.

A typical offset radiator tube-fin unit of the radiator is 1.635 inches wide and has a coolant tube diameter of 0.18 inch and a thickness of 0.03 inch for the composite copper-stainless steel fin. The primary meteroid armor protection is 0.089 inch thick and 0.021 inch of bumpered armor protection surround each coolant channel.

The weight of the twelve radiator panels, which total 661 square feet in area, and the associated headers is 1335 pounds when dry. The header description is included in the discussion of the feed line network portion of the loop piping.

The main heat rejection piping is made up of the reactor header configuration, the radiator feed line network, and the intermediate piping. The coolant inlet plenum is at the forward end of the reactor and the exit plenum at the rear end. Header arrangements distribute and collect the coolant to each plenum. The inlet header is a circular torus of rectangular cross section, located at the rear and outside the outer diameter of the reactor, see Figure 7-1.

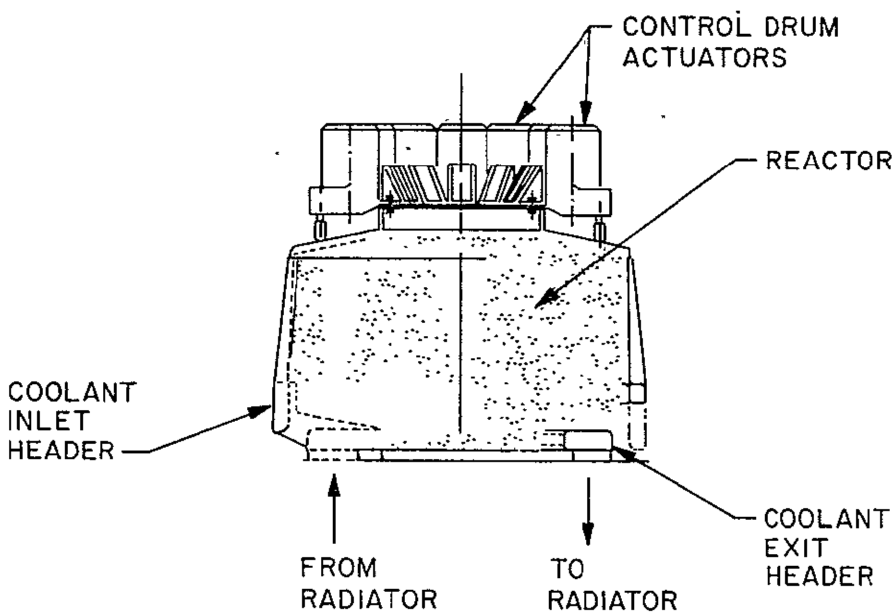

Figure 7-1. Coolant Header Arrangement for Externally-Fueled Reactor

Two rectangular shaped ducts, 2 by 5 inches in cross section, transport the re... coolant across the shield surface in a curving path. The rectangular configuration is utilized to minimize the depth of the channel made in the shield and to lessen the radiation dosage penetrating the resultant shield voids. These ducts connect to the feed lir network which distributes the coolant to the twelve radiator panels, as shown on Figur 7-2. The total weight of the radiator feed line network plus the connecting piping to th

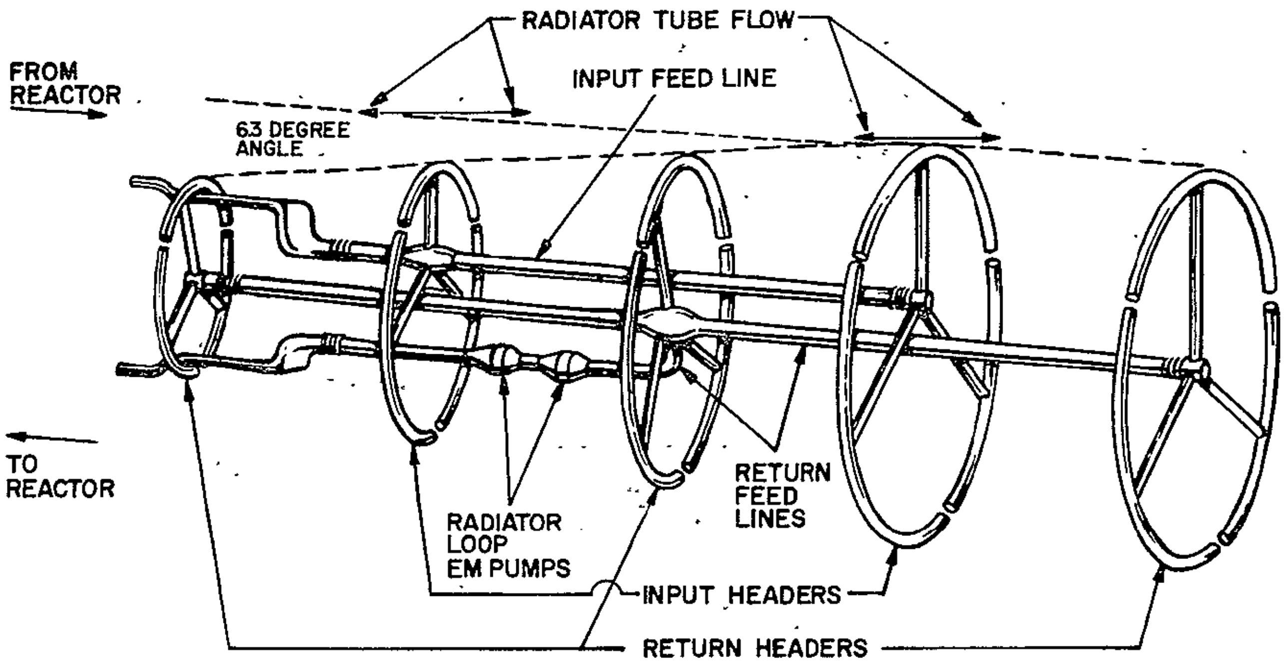

Figure 7-2. Main Radiator Feed Line Networl

reactor is 198 pounds when 0.06-inch thick stainless steel duct material is used. The total ducting weight for the heat rejection system is 295 pounds.

As shown in Figure 7-2, two EM pumps are installed in the main heat rejection pipe loop. Only one of the pumps is in operation at any one time with the second pump being in standby condition. Each pump is a dc conduction pump, similar in concept and configuration to the one shown in Figure 7-3. The coolant duct is divided into ten parallel channels which are arranged in circular fashion as shown on the figure. The parallel coolant ducts are flattened into a very thin rectangular configuration and each of these duct sections traverse the magnetic field of a magnet ring. A coil of heavy wire wrappe around a magnet ring and carrying a dc current produces the magnetic field

The EM pumps for the reactor loop use ten parallel duct segments, with each segment in the pumping region being 0.125 by 3.83 inches in cross section and 1.2 inches long in the direction of coolant flow. The 1.2-inch thick magnet ring has inner and outer

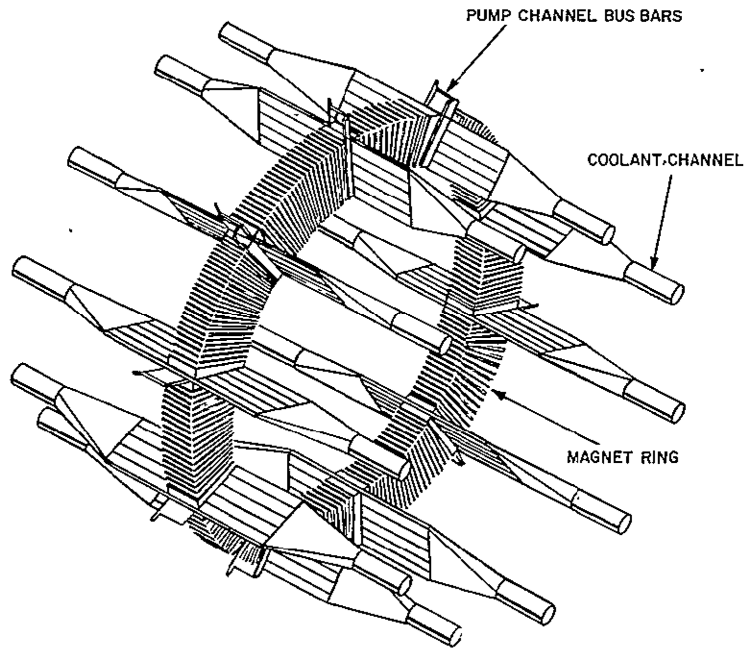

Figure 7-3. Schematic Diagram of a DC Powered EM Pump

diameters of 3.35 and 6.15 inches, respectively. Copper lead approximately 0.033 square inch in area forms the energizing coil for the magnet. The total weight of each EM pump including transition ducts and insulation is 50 pounds.

The electrical power requirement for the pump is 2.8 kW supplied at approximately 10 volts and 280 amperes.

The total inventory of NaK coolant contained in the heat rejection system is 650 pounds; 75 pounds in the reactor, 195 pounds in the main radiator panels, and 490 pounds in the reactor headers, the radiator feed line network and connecting ducts, the EM pump, and the accumulators.

Thermal insulation protects the shield from the hot heat rejection ducts traversing its surface, and the rear section of the vehicle from the main radiator. The latter protection includes a radiation barrier across the entire cross section of the vehicle at the back end of the main radiator, a fibrous mineral type of insulation under the auxiliary radiator, and thermal conduction barriers at the front and rear mating rings of the main radiator. The combined weight of all the insulation is 76 pounds.

7.1.1.3 Electrical Subsystem

The electrical subsystem includes that portion of the spacecraft electrical network which processes and supplies the hotel power required to operate the powerplant. It also includes the electronic components which monitor and automatically control the actuator drives of the reactor, and the pumps of the various heat rejection loops in the powerplant. The power conditioning weight, based on the analysis shown in Section 6 for the auxiliary PC units, is calculated to be 45 pounds for the hotel power requirements. The corresponding portion of the PC radiator (about 10 square feet) is 20 pounds. The weight of cabling to the PC units, pumps, and other components is another 20 pounds while the electronic powerplant control modules are estimated to weigh 50 pounds.

7.1.1.4 Auxiliary Coolant Loop

The auxiliary loop provides cooling for the neutron shield and the electrical and magnetic components of the main heat rejection loop EM pump. Figure 7-4 is a schematic representation of the auxiliary loop which includes a radiator, pumps, accumulators, cooling coils for the neutron shield, and all connecting piping. The auxiliary loop pump pressurizes the cooled fluid exiting the radiator and forces it, in sequence, through cooling passages in the main EM pump, the cooling channels in the lithium hydride shield, and the auxiliary radiator. The pump is a dc powered single duct unit. The weight of both pumps, the operating and the redundant pump, is 20 pounds. The auxiliary radiator encircles the spacecraft in belt-like fashion between the main radiator and the PC radiator. It consists of a single coolant tube attached to a 2-inch wide copper-stainless steel fin and weighs 10 pounds. Accumulators weigh another 10 pounds.

The largest weight item in the loop is the connecting piping because of some 75 feet of overall length. The piping, which is 1 inch in diameter, weighs 35 pounds and the total loop coolant inventory is another 25 pounds.

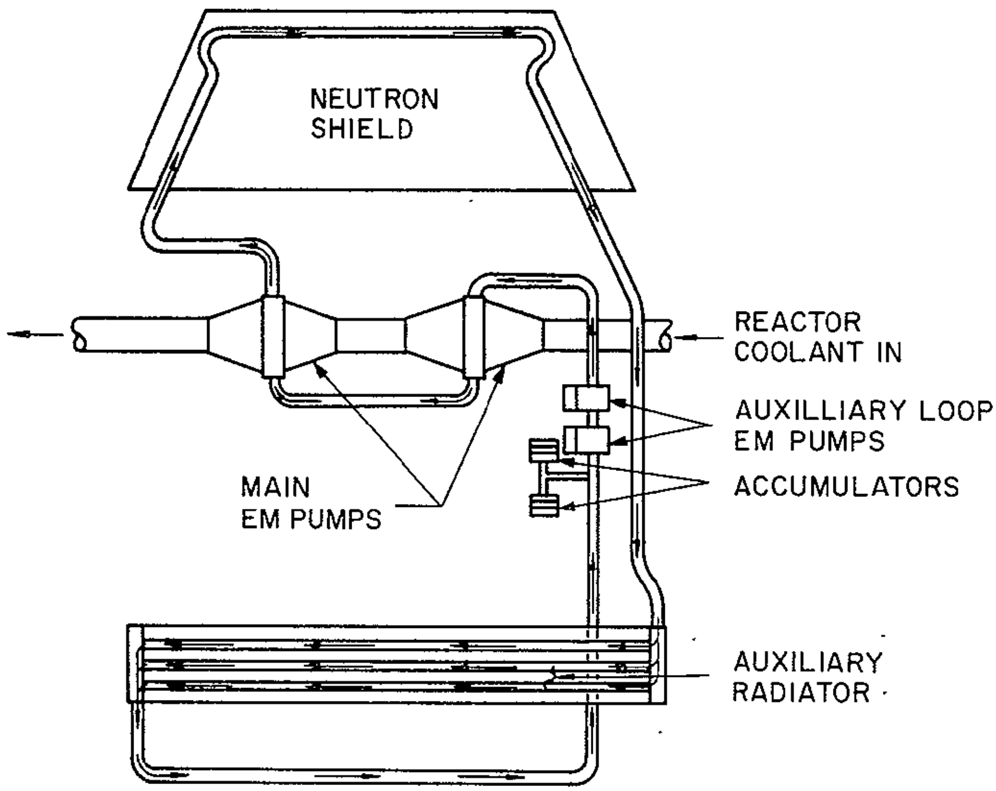

Figure 7-4. Schematic Representation of Auxiliary Loop

7.1.1.5 Powerplant Support Structure

The powerplant support structure includes all the spacecraft structure required exc that needed for the propellant tanks, the payload, and the thrusters. It includes:

a. Reactor support

b. Shield support

c. Main radiator stiffeners and mating attachments

d. PC radiators stiffeners and mating attachments.

The reactor support structure is a sheet metal frustum, imbedded in the neutron shield, and attached at its base to the rear edge of the lithium hydride can. The smaller diameter of the frustum is attached to the front plate of the lithium hydride can opposite the reactor. Attachment rings on both the upper and lower bases of the frustum provide the necessary connecting fixtures. The support frustum is constructed of 0.06 thick stainless steel, lightened by 50 percent by hole punchouts. The total weight of the frustum and L-shaped attachment rings is 40 pounds.

Shield support is provided by a lateral surface can wall thickness of 0.08 inch stainless steel, coupled with four circumferential Z-shaped stiffeners. The combined weight of the can wall and stiffeners is 67 pounds.

Structural additions to the main radiator section of the spacecraft include mating attachment rings, circumferential stiffeners and longerons. Mating rings are needed for the four main radiator bays which weigh a total of 140 pounds. The rings are J-shaped and made from 0.08 inch thick sheet. A Z-shaped frame or stiffening ring is required in each of the two rearward radiator bays. Constructed of 0.06 inch thick stainless steel, the stiffeners weigh a total of 30 pounds. Four L-shaped longerons in each bay provide buckling support for the radiator. Constructed of 0.125 inch thick stainless steel, they weigh a total of 165 pounds for the entire radiator.

The power conditioning radiator also has structural additions in the form of mating rings, stiffeners and longerons. In addition, a portion of the radiator surface is blocked by the low-voltage cables. This blocked surface does not dissipate heat, but it must be present to provide structural rigidity to the radiator. Consequently, the weight of this blocked surface, 65 pounds, is attributed to powerplant structure.

The two mating rings of the PC radiator, each formed from 0.08 inch thick aluminum, weigh a total of 35 pounds. Z-frames, or stiffeners, located at four axial locations and constructed of 0.094 inch thick aluminum weigh a total of 50 pounds. Twenty-four longerons, T-shaped and constructed of 0.156 inch thick aluminum, run the length of each PC radiator panel. The weight of these longerons is 210 pounds. The total weight of all structural components in the PC radiator location is 360 pounds.

7.1.2 THRUST SUBSYSTEM GROUP

The thrust subsystem group includes the subsystems which transfer and convert the electrical power generated by the reactor to propulsive power. These subsystems are the low and high voltage cable networks, the high voltage supply PC units with corresponding radiator panels, and the thruster ion engines.

7.1.2.1 Ion Engine Subsystem

The ion engine subsystem, including the individual engines and vector control hardware has been designated by JPL. The 37 engine units weigh 585 pounds, the vector control assembly 550 pounds, and miscellaneous hardware another 100 pounds.

7.1.2.2 Low Voltage Cables

The low voltage cable assembly consists of the reactor leads and low voltage bus bars which transport the reactor electric power output to the high voltage supply PC units and to the special payload and thruster PC modules. (The hotel load low voltage distribution system is included in the powerplant subsystem weight group.) The initial, high temperature copper reactor leads exit the reactor through the walls of the coolant outlet plenum.

Both bus bars extend down the outer surface of the shield and main radiator components into the power conditioning radiator section. The bus bars extend axially along the PC radiator with 4 pairs of leads turning 90 degrees at separate axial locations, to extend circumferentially to individual PC modules.

The high temperature copper reactor leads located near the reactor weigh less than three pounds including ceramic bead insulators. The aluminum bus bars are rectangular in cross section, 0.165 inches by 0.28 inches, with a mean length of 44 feet. The total weight of these bus bars is 195 pounds with an additional weight of 28 pounds in ceramic insulation. Multifoil insulation of Al-Ni composition is placed between the bus bars and the high temperature surfaces, the main radiator and neutron shield, which the aluminum bus bar traverses. The weight of this insulation is 80 pounds.

Two pair of aluminum bus bars extend into the payload and thruster bays carrying power to the respective PC units. The weight of this additional length of cable, plus insulation, is less than 6 pounds.

7.1.2.3 High Voltage Cables

The high voltage cables are the 3100-volt lines from the main power conditioning modules to the ion engines. A pair of leads, one positive and one negative, extend from each module to each ion engine. The total weight of these leads is 15 pounds which includes the ceramic insulation.

7.1.2.4 Power Conditioning Modules

The power conditioning subsystem includes 37 high voltage supply units (one per ion engine) plus the special PC modules. The high voltage supply modules, which weigh a total of 1390 pounds, are based on the concepts and component definitions described in Section 6.2.2 for these units. The total weight of the special ion engine PC modules is 270 pounds.

7.1.2.5 Power Conditioning Radiators

The radiator surface corresponding to the 37 high voltage supply PC modules is 470 square feet. (The rest of the radiator is chargeable to the hotel load PC units in the powerplant subsystem group.) The weight of this radiator surface area, based on a 0.115-inch thickness for the aluminum panels, is 745 pounds.

The special ion engine PC radiator, which dissipates 1.9 kW, weighs 85 pounds.

7.1.2.6 Ion Engine Structure

The payload and ion engine bays require mating rings, stiffeners, and longeron stringers for support structure. The mating rings weigh 23 pounds, the stiffeners weigh 3 pounds, and the longeron weigh 50 pounds. Of this total, approximately 40 pounds is chargeable to the thrust bay.

7.1.3 PROPELLANT SYSTEM

The propellant system consists of the mercury propellant and the corresponding tanks, feed lines, and structural attachments. Of the total 14,500 pounds of mercury specified in the design guidelines, approximately 4250 pounds are located in a tank behind the neutron shield to act as protection for the spacecraft from the reactor gamma radiation. The tank is a conical cylinder constructed of 0.10-inch thick stainless plate at the top and bottom and 0.08-inch thick plate for the lateral surface. The total weight of this tank with radial steel stiffening bars on the rear face and on internal expulsion bladder for the propellant is 160 pounds.

A cylindrical tank located in the thrust bay contains the remaining 10,250 pounds of propellant. The weight of this tank with mercury feed lines to the ion engines is 70 pounds. Attachment brackets for both propellant tanks total 15 pounds.

7.1.4 SPACECRAFT PAYLOAD COMPONENTS

The delineation of the payload science package, communications equipment, spacecraft guidance and control, etc., has been provided by JPL. The weight of conduction fin radiator corresponding to the combined payload heat rejection requirements is 25 pounds. The weight of structural stiffeners and longerons attributable to the payload bay is an additional 25 pounds.

7.1.5 LAUNCH COMPONENTS

Two special components are required for the spacecraft during the launch phase of the mission; an adapter cone attaches the spacecraft to the launch booster, and a flight fairing or shroud protects the spacecraft from aerodynamic pressure loads and heating during the launch trajectory. The adapter cone, shown on the layout drawing, (Figure 1-1) surrounding the ion engines and stowed antennas weighs 250 pounds. The launch shroud, which is 66 feet long, weighs 3500 pounds. Since the shroud is jettisoned after peak aerodynamic pressure and heating conditions occur, but before booster cutoff, only a fraction of the shroud weight is chargeable as payload weight reduction. This fractional shroud weight or payload penalty is 825 pounds for the externally fueled reactor spacecraft system (24 percent).

7.2 FLASHLIGHT POWERPLANT/SPACECRAFT

The reference flashlight powerplant and spacecraft design is extrapolated from the results obtained with a thermionic computer code optimization for a 300 kWe reactor output system. Important conditions assigned for the computer analysis and for the reference design are:

a. A reactor outlet temperature of 1350°F

b. A two loop, in-series, heat rejection system

c. A relative radiator arrangement having the power conditioning radiator behind the shield and the main radiator at the rear of the spacecraft

d. Aluminum as the low voltage cable composition

As shown in Table 1-5, a reactor output power of 318 kWe is required to supply a net power of 240 kWe to the thruster subsystem. Cable losses of 20.5 kWe and power conditioning losses of 35.32 kWe occur in the low voltage end of the electrical circuit, with the remaining 262.18 kWe appearing as high voltage power from the PC components. Most of this high voltage power is at 3100 volts, and provides 223 kWe to the thruster ion engines. The remaining high voltage power, which is at 250 volts, is divided almost equally between the payload and special ion engine PC requirements, and the powerplant hotel load requirements.

The spacecraft is a long, narrow vehicle, 84.15 feet long and 9.2 feet in diameter, made up of a conical front end section, having a 7.4-degree half angle, attached to a cylindrical rear section. The reactor is located at the apex of the front section cone to provide maximum separation distance from the payload, which is at the rear of the cylindrical section, and to assure minimum volume for the shadow shield.

The neutron shield is located as close as possible to the reactor, again to provide minimum shield volume and weight, with a portion of the mercury propellant located in a tank behind the neutron shield to act as gamma shielding.

The power conditioning modules and power conditioning radiator section are located directly behind the shield and propellant tank to minimize the length and, hence, the power losses in the low voltage cable. This is required due to the low voltage, 14 to 16 volts, characteristics of the flashlight reactor (see Section 3.3). Individual PC modules are distributed uniformly on the surface of the PC radiator, one module per pair of reactor fuel elements and low voltage cables. The cables are strung along the outer surface of the shield PC radiator surface so that they can radiate their I^2R power losses directly to space.

The PC radiator occupies most of the conical surface of the spacecraft plus 9.7 feet of the cylindrical section. A very short section auxiliary radiator surface acts as a thermal buffer between the low temperature PC radiator and the high temperature main radiator which covers most of the cylindrical section surface. The reactor waste heat is transported to the main radiator in two stages. The first loop pipes the reactor coolant, NaK, outside the shield to a heat exchanger placed between the neutron shield and the gamma shield (forward propellant tank). A second NaK loop carries the heat along the outer surface of the PC radiator to the main radiator.

7.2.1 POWERPLANT SUBSYSTEM GROUP

The propulsion system is made up of the power plant subsystem and the thruster subsystem. The power plant subsystem, in turn, comprises all the subsystems which generate the propulsion power.

7.2.1.1 Reactor Subsystem

The 318 kWe reactor is 2.37 feet in diameter, 2.96 feet long and weighs 3060 pounds in the dry condition. Twelve S8DR control actuators (SNAP-8 Ground Prototype), modified for eccentric output drive, are mounted on the front end of the reactor. These actuators are radiatively cooled and weigh a total of 230 pounds. They drive radial reflector segments in an axial direction to effect reactor control by varying neutron leakage.

Fuel element extensions, electrical leads, cesium vapor feed tubes and reactor coolant piping all emerge from the back end of the reactor into the bay between the reactor and shield. The weights of the cesium vapor feed lines and the cesium resevoir are included in the reactor weight while the coolant header weights are included in the reactor loop subsystem and the reactor lead weights are included in the low voltage cable weight. A cesium heat pipe radiator removes excess heat from the cesium reservoir and dissipates it by radiation. This radiator, which weighs approximately 10 pounds and has approximately four square feet of surface area, encloses a portion of the equipment bay which measure 15 inches in axial length.

7.2.1.2 Shield Subsystem

The shield subsystem consists of a block of lithium hydride acting as a neutron shield. A tank of mercury propellant is the main gamma shield but its weight is charged to its primary function as engine propellant.

The neutron shield is an internally supported tank filled with lithium hydride. Its configuration is a frustum of a cone, 26.4 inches thick with base diameters of 44.5 and 51.5 inches and its weight is 1610 pounds.

The total heating rate in the shield subsystem is approximately 1.8 kW with great majority of this heat being deposited in the front one-foot thickness of the neutron shield. This heat is removed by the auxiliary cooling loop.

The reactor loop piping races a helical path just below the lateral surface of the neutron shield. The resultant holes in the shield barrier are covered with plugs of canned lithium hydride on the front end and rear faces of the neutron shield. Similar plugs of tungsten, 3.5 inches thick and weighing 265 pounds; cover the voids through the mercury tank caused by the passage of the radiator loop piping.

7.2.1.3 Reactor Loop Subsystem

The reactor loop subsystem is shown semi-schematically on Figure 7-5. The loop consists of two coolant headers and coolant feed pipes at the rear face of the reactor, two EM pumps and three accumulators in the heat exchanger bay and the piping between the reactor and heat exchanger. The heat exchanger itself is arbitrarily assigned to the radiator loop subsystem.

As shown on Figure 7-5 the headers are crescent shape tori which have an average width of 3.5 inches, a depth of 2 inches and an approximate diameter of 30 inches. Constructed of 0.10 inch thick stainless steel plate, each header weighs 30 pounds.

Six equally spaced 2 inch diameter pipes, weighing 9 pounds, distribute the coolant to the reactor from each header. A single duct, having a cross section area equivalent to a 4.3 inch round pipe, connects each header with the heat exchanger group. The total length of this ducting is 12.5 feet long and with a wall thickness of 0.06 inches, weighs 34 pounds.

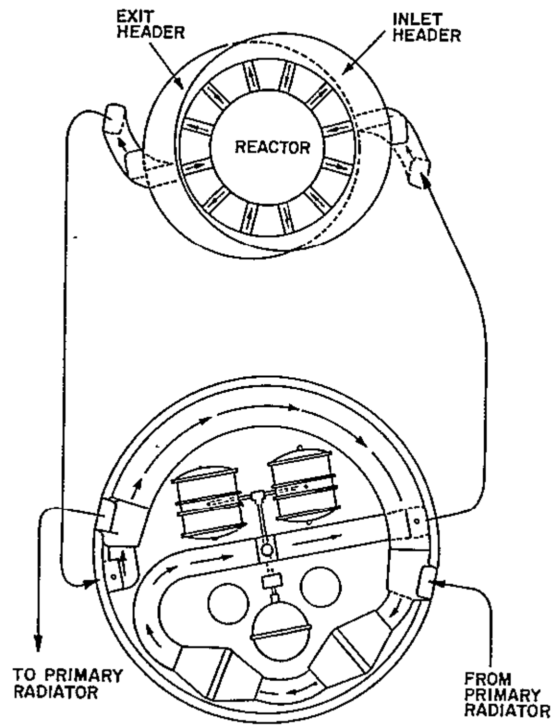

Figure 7-5. Schematic of Reactor Loop

Two EM pumps in series, one operating and one redundant, pump the reactor coolant. These pumps are similar in design and concept as those described in Section 7.1.1.3 for the externally fueled power plant. The electrical power requirements for each of the pumps in the flashlight reactor loop is 8.06 kW supplied at 10 volts and 800 amperes.

The total coolant weight in the reactor loop is 280 pounds; the reactor holds 133 pounds, the tube side of the heat exchanger contains 27 pounds and the remaining 120 pounds is distributed in the piping, headers and EM pump ducts.

Multifoil insulation is used around sections of the reactor piping to protect adjacent equipment from the high temperatures of the coolant. The insulation is placed on the rear face of the neutron shield and the front face of the propellant tank for thermal protection from the heat exchanger, pumps, etc. Additional insulation surrounds the loop piping and headers to protect the shield, cesium system and electrical leads. The total weight of insulation in the reactor loop region is 65 pounds.

7.2.1.4 Radiator Loop Subsystem

The radiator loop transfers the reactor waste heat from the reactor loop and transports it to the main radiator for dissipation to space. The loop consists of the following components:

a. Heat exchanger

b. Main radiator

c. Piping with EM pumps and accumulators

d. Protective thermal insulation.

The heat exchanger is a tube and shell, counter-cross flow, unit with the hot reactor NaK-78 coolant flowing inside the tubes and the cooler radiator NaK-78 coolant in combination flow, across and counter to the tube flow. The characteristics of the heat exchanger are as follows:

Heat transfer rate	2520 kW
Heat exchanger length	56.5 inches
Heat exchanger diameter	4.6 inches

Tube diameter	0.2 inches
Number of tubes	433
Shell thickness	0.10 inches
Tube wall thickness	0.02 inches
Tube side pressure drop	1.67 psi
Cold side pressure drop	4.37 psi

The weight of the dry heat exchanger is 180 pounds.

The main radiater has a total area of 945 square feet divided into four axial bays with three panels per bay. Each panel covers one-third of a cylindrical lateral surface (120° of arc) and is 9.8 feet wide and feet in axial length. Sixty-five coolant tubes, which run the length of each panel are joined by solid fin sections of copper-stainless construction. The copper-stainless steel fins are 0.03 inches thick with the armor tubes spaced on 1.752 inch centers. The coolant channels are 0.18 inches in diameter with 0.095 inches of primary armor protection and 0.0244 inches of bumpered armor protectioı The total weight of all the panels plus their headers, which will be described in the next paragraph, is 2190 pounds.

The network of feed lines and headers which distribute the radiator loop coolant to the radiator panels is shown on Figure 7-6. Five rings of headers distribute the coolant to the twelve radiator panels. Each header ring is separated into three sections corresponding to the three panels per radiator bay. The second and fourth ring of headers dispense the incoming coolant with the second header ring feeding the first two bays and the fourth ring feeding the last two bays. The middle header ring collects the coolant from the two central bays while the two end header rings collect the coolant from the respective end bays. The three middle header rings, which service two bays are 1.67 inches in diameter, and the two end rings are 1.18 inches in diameter. As noted above, the weights of these headers are included in the radiator weight.

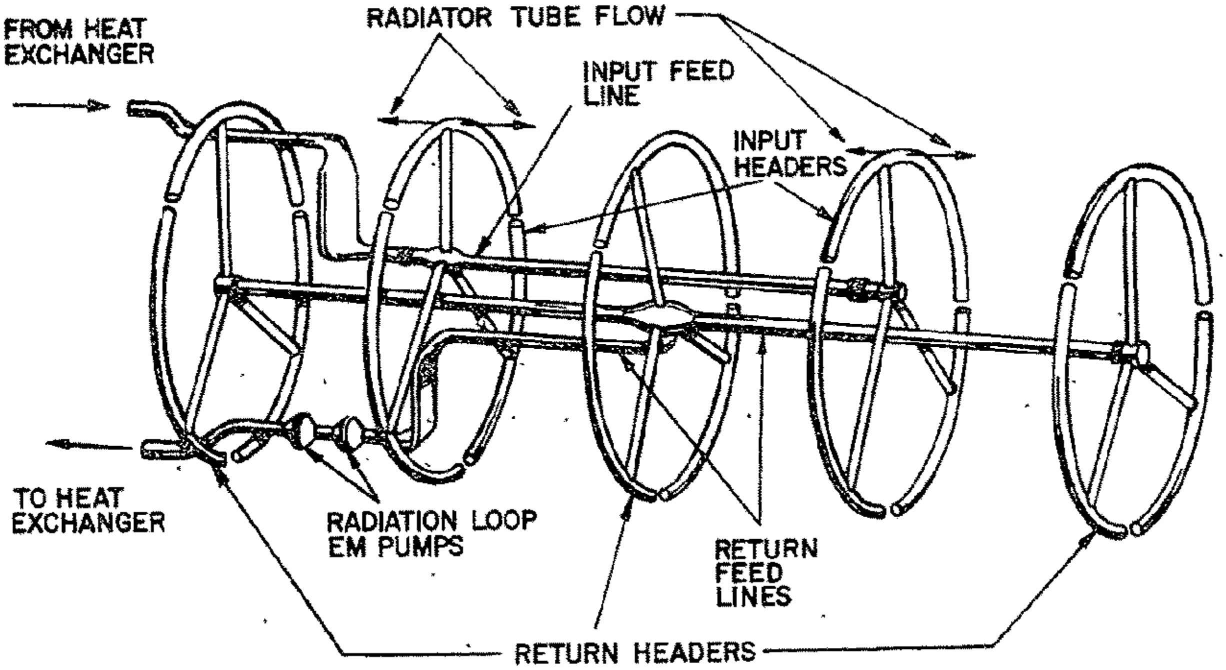

Figure 7-6. Schematic of Main Radiator Loop

The radiator feed line network consists of the axially directed input and return feed lines plus the radial, spoke-like feeders running to each header. These latter header feeders are 1.75 inches in diameter, while the input feed line has a 2.9 inch diameter and the return feed line is 2.04 inches in diameter. The piping to and from the heat exchanger up to the junction with the feed lines is 4.0 inches in diameter.

Two S-shaped duct segments of flat rectangular cross section are located in the radiator loop piping, as shown on Figure 7-6. These duct segments bend to accommodate the relative expansions of the piping between the heat exchanger and the radiator and the radiator itself. Additional bellows in the input and return feed lines take up expansion motion between the individual bays of the radiator.

The total weight of the radiator loop piping including the radiator feed lines and expa sion bellows is 440 pounds.

Two EM pumps in series, similar to those previously discussed, pump the radiator loop coolant. The weight of each pump is 45 pounds.

Two dynamic and one static accumulator regulate the coolant expansion-pressure level conditions in the radiator loop. The dynamic accumulators are the same size and weight as those in the reactor loop. The static accumulator is approximately 1 foot in diameter and weighs 60 pounds for a total accumulator weight of 100 pounds.

The coolant inventory in the radiator loop consists of 263 pounds in the radiator, 112 pounds in the shell side of the heat exchanger and 608 pounds in all the piping.

Insulation surrounds radiator loop piping and separates the main radiator section of the vehicle from the auxiliary radiator and payload sections. The total weight of this insulation is 210 pounds.

7.2.1.5 Electric and Controls Subsystem

The power plant electric system consists of the hotel PC units and their radiators, plus the cabling to the pumps and equipment using the power. Special PC modules convert a 250 volt input power to the voltages required for the EM pumps and the reactor controls. The cesium heater requires no additional power conditioning. Fi 7-7 shows the power distribution, voltages and PC unit efficiencies in the hotel load circuit. The PC units have a specific weigh of 12 lb/kW so the total PC weight is 18 pounds. The weight of the corresponding 0.10 inch thick radiator panels, which tota 35 square feet in area, is 60 pounds. The total weight of cabling, including 10 mils insulation, between the hotel PC modules and the user equipment is 45 pounds. Power plant control equipment is assumed to weigh 50 pounds.

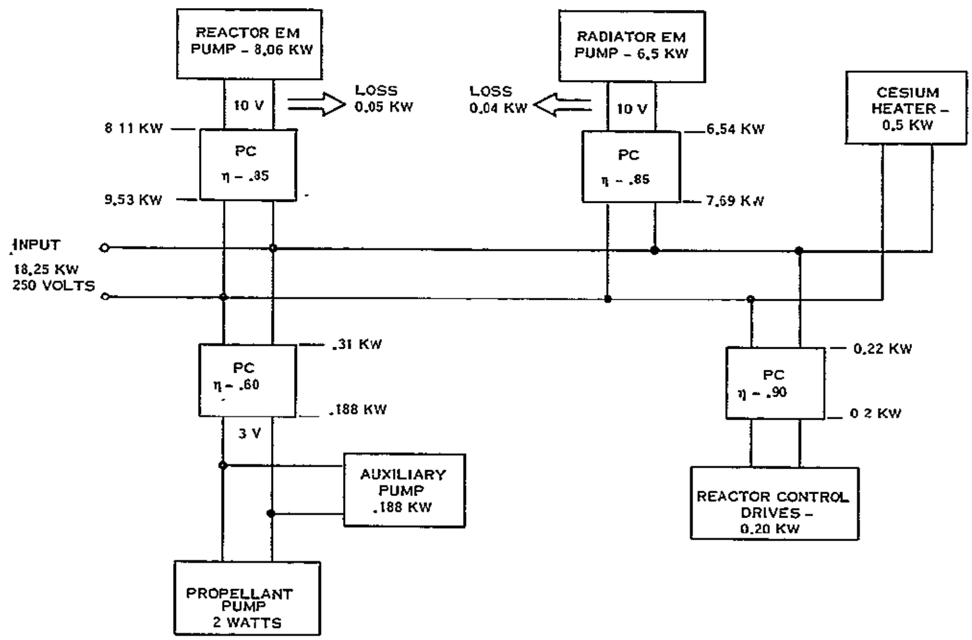

Figure 7-7. Hotel Load Power Distribution

7.2.1.6 Auxiliary Cooling Loop

The auxiliary cooling loop provides a thermal heat rejection mechanism for those system components which have temperature limitations lower than the temperatures in the main heat rejection system and higher than the electronic components in the spacecraft. These intermediate components are the electrical and magnetic sections of the EM pumps and the netron shield. Figure 7-8 is a schematic layout of the auxiliary cooling loop. Self cooling EM pumps force the NaK-78 coolant through cooling passages in the reactor EM pump electrical section, then through cooling passages in the frontal regions of the neutron shield. The NaK is then at it's hottest temperature and is passed through the auxiliary radiator. The cooled flow is then circulated through

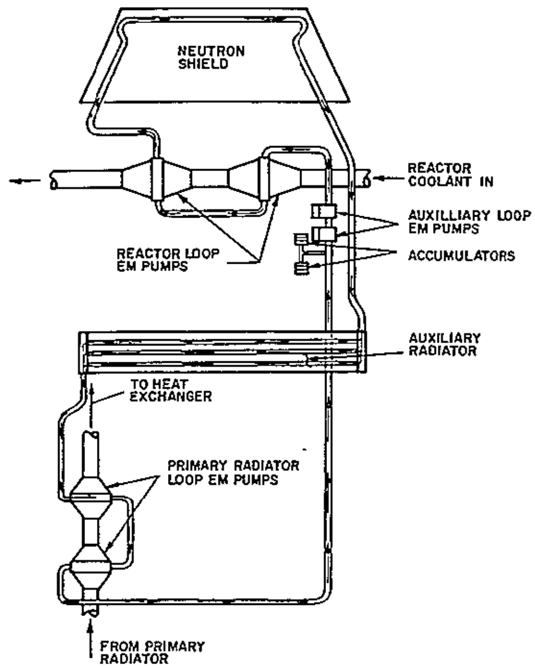

Figure 7-8. Schematic of Auxiliary Cooling Loop

the cooling passages of the radiator loop EM pump and returned to the auxiliary pump to complete the circuit. Accumulators control the expansion and pressure level of the coolant as in the other heat rejection loops.

The auxiliary radiator is a narrow fin band, containing a single cooling channel, located between the low temperature PC radiator and the high temperature main radiator. The radiating surface is ten square feet in area and only 4.5 inches wide. Its weight is approximately 20 pounds.

The total length of the 1.0 inch diameter piping is 71 feet and its dry weight is 33 pounds. The coolant weight is 20.5 pounds in the piping and 4.5 pounds in the radiator and pumps for a total weight of 25 pounds. Two accumulators approximately 6 inches in diameter and 6 inches long weigh 5 pounds apiece. EM pumps are estimated to weigh 10 pounds apiece. The total weight of the auxiliary loop is 110 pounds.

7.2.1.7 Power Plant Support Structure

The power plant support structure includes all the spacecraft structure required except that needed for the propellant tanks and the payload and thruster bay sections. It includes:

a. Reactor and shield support

b. PC Radiator stiffeners and mating rings

c. Main Radiator stiffeners and mating rings.

The reactor support is a sheet metal section of a cone buried inside the lithium hydride neutron shield and an attachment ring on the front face of the shield. The sheet metal cone is formed from 0.06 inches thick SS sheet and is reduced in weight by the use of lightening holes. The total weight of this support cone and the attachment ring is 56 pounds.

Sixty mil thick, L-shaped stiffening rings at the outer rim edges of the conical shield are required to achieve required rigidity in the neutron shield can. In addition, approximately 0.08 inches of stainless steel meteoroid protection is required on the neutron shield surface areas which are not covered by the low voltage cable. The combined weight of the stiffening rings and added skin thickness of meteoroid protection is slightly less than 50 pounds.

The conical section of the power conditioning radiator is actually a six-sided prism, while the cylindrical section is actually twelve-sided. A transition section, approximately 5 feet in axial length connects the six and twelve-sided sections. The PC radiator is split in half axially by the main radiator heat rejection piping running down opposite sides of the PC radiator surface. Therefore, a U-shaped support channel joins the two halves of the radiator. The thin 0.10 skin of the PC panels does not have sufficient strength to provide launch support for the heavy weights of the reactor,

shield and propellant tank in the front end of the vehicle. Consequently, longerons and circumferential stiffening rings are added to supply the required strength.

Two U-shaped rings, 0.04 inch thick and weighing 8 pounds, provide mating connections for the twelve-sided cylindrical section of the PC radiator. A similar ring, weighing 4 pounds, allows the conical section of the radiator to be joined with the transition ring. Z-shaped stiffening rings, one in the cylindrical section and two in the conical section, weight a total of 15 pounds.

The U-shaped beams which connect the two halves of the PC radiator around the main radiator loop coolant pipes are constructed of 0.02 inch thick aluminum, and weigh a total of 25 pounds. T-shaped longerons, 14 in the cylindrical section and 8 in the conical section, provide the axial compressive strength capability. These members of 0.060 inch thick aluminum, weigh a total of 120 pounds.

A portion of the PC radiator panels can not radiate heat since they are covered by the low voltage cable. This fraction of the radiator still must be present to provide structural continuity so the weight of the blocked area is attributed to power plant structure. That weight of blocked area is 225 pounds.

A transition ring bridges the surface area occupied by the auxiliary radiator to connect, structurally, the main radiator to the power conditioning radiator. This transition ring, shaped like two U-channels placed back-to-back and joined by a connecting web, is formed from titanium plus Min-K* insulation and weighs 65 pounds. It also provides the significant function of a thermal barrier.

Stiffening rings to resist launch bending loads and mating rings are added to each bay of the main radiator. The mating rings at each end of each bay total 299 pounds. The Z-shaped stiffening rings are placed close together in the rear radiator bay and relatively far apart in the forward radiator bay, as the buckling loads decrease with

*T.M. Johns Manville Co.

increasing separation from the base of the spacecraft. The total weight of the fourteen stiffening rings is 126 pounds. Additionally, 650 pounds of longerons are required, added as increased tube wall thickness for extra, although unnecessary meteorid protection. The total structural weight is 1075 pounds in the main radiator bays. The total weight of all the powerplant structural components is 1655 pounds.

7.2.2 THRUST SUBSYSTEM GROUP

The thrust subsystem includes the ion engine subsystem, the low and high voltage power cables, the high voltage and special ion engine power conditioning subsystems and the related power conditioning radiators. These individual subsystems will be described in the following paragraphs.

7.2.2.1 Ion Engine Subsystem

The ion engines and TVC unit which comprise the Ion Engine Subsystem are identical to the components described for the externally fueled reactor spacecraft in Section 7.1.2.1.

7.2.2.2 Low Voltage Cables

A low voltage cable assembly is a two component arrangement in series; a copper cable extending from the reactor fuel element extension to the front rim of the neutron shield, and an aluminum bus bar extending from the junction with the copper cable to a power conditioning module. A low voltage cable assembly is attached to each of the 216 reactor fuel elements. Two fuel elements, two LV cable assemblies and a power conditioning module make up a common low voltage electrical circuit.

The copper reactor leads are 0.327 inches in diameter and have an average length of 18 inches. Ceramic bead insulation prevents electrical short circuiting and allows bundling of the leads for bracing and support. The leads are attached mechanically and brazed to the aluminum bus bars.

Each aluminum bus bar is rectangular with cross section dimensions of 0.39 inches by 0.667 inches. The lengths of the bus bars vary from eight feet to 35 feet with an average length of 23.6 feet. The cross section dimensions and performance evaluations are based on the average length.

The bus bars run axially along the conical surface of the shield, bend in a S-shaped curve at the juncture of the propellant tank and power conditioning radiator, proceed axially along the surface of PC radiator, then bend 90^{o} in the plane of the radiator panel to attach to the PC module provided for each TFE pair. The busses are grouped in six bundles, one for each of the six sides of the conical section of the radiator. A thin layer of ceramic on the surfaces of the bus bars provides the required electrical isolation. Ceramic coated metal braces attach and support the bus bars to the various spacecraft components. In the shield and propellant tank areas, thermal insulation protects the bus bars from higher temperatures existing in those components.

The weight of all the copper reactor leads is 105 pounds while the total weight of the aluminum bus bars is 1515 pounds. The ceramic surface coating weighs an additional 60 pounds.

7.2.2.3 High Voltage Cables

The high voltage cable subsystem consists of the 3100 volt lines between the main power conditioning modules and the ion engines, and the 250 volt lines between the main PC modules and the special payload and thruster PC modules.

The 3100 volt cabling consists of four separate wires, forming two complete circuits. The extra circuit provides greatly increased reliability with negligible penalty. Each aluminum wire strand is approximately 0.2 inches in diameter, 130 feet long and weighs 6.2 pounds. The cable starts at the rear end of one side panel of the PC radiator, runs forward the entire length of that panel, then returns down the length

of an adjacent panel. This procedure occurs across the six side panels of the PC radiator. The cable then traverses the axial length of main radiator and payload sections to reach the ion engines. The wire strands are clamped in ceramic troughs which support and electrically insulate the feed and return strands from each other and from the spacecraft. Thermal insulation between the ceramic troughs and the main radiator surface keep cable temperatures at acceptable levels.

The 250 volt line to the payload and thruster PC modules is of similar 4 strand construction, follows the same path and is supported in the same ceramic trough as the 3100 volt line. Each wire strand is 0.3 inches in diameter and weighs 9 pounds for a total weight of 35 pounds. The total insulation weight on both the 3100- and 250-volt cables is estimated at 10 pounds.

7.2.2.4 Power Conditioning Modules

One hundred and eight power conditioning modules, constituting the high voltage power supply, are distributed on the inner surface of the PC radiator panels. The circuit concepts and component definitions follow the designs formulated in Section 7. On the basis of 8.9 lb/kW of input power, the high voltage supply PC modules weigh 2640 pounds.

The weights of the special ion engine PC units at 270 pounds were supplied by JPL. The thruster isolation weights are estimated at 310 pounds.

7.2.2.5 Power Conditioning Radiators

The power conditioning radiator as shown on the layout drawing, rejects the heat generated in the high voltage supply and the hotel load power conditioners. The radiator weight corresponding to the hotel load PC waste heat generation has been included in the power plant electric subsystem reported in Section 7.2.1.5. The remaining radiator area, 558 square feet, is attributable to the high voltage supply PC. The weight of this latter portion is 770 pounds based on 0.10 inch thick aluminum radiator panels.

The radiator heat loads from the special ion engine PC modules and isolation units are 1.7 and 1.25 kW, respectively. The corresponding radiator areas and weights are 36 square feet and 70 pounds for the PC modules, and 26 square feet and 50 pounds for the isolation units.

7.2.2.6 Thruster System Structure

Two mating rings, a circumferential stiffening ring and thirty seven longerons are required in the payload-thrust bay for spacecraft assembly and launch support. The total weight of these structural members is 100 pounds of which 65 pounds is chargeable to the thrust section.

7.2.3 PROPELLANT SYSTEM

The propellant system is made up of mercury propellant with associated tankage and support structure. The propellant weight is 14,500 pounds as in the externally fueled reactor spacecraft. Of this weight 10,800 pounds is contained in a conical tank behind the heat exchanger bay acting as a gamma shield. The tank is 9 inches thick and has a mean diameter of 56 inches. Eighty mil thick plate is used for the conical areas of the tank for meteoroid protection while the front and rear faces of the tank are 0.10 inches thick. The total weight of the tank including radial stiffeners is 210 pounds.

A cylindrical tank located in the thruster bay region holds the remaining 3700 pounds of propellant. The weight of this tank is 35 pounds and the weight of mounting brackets for both tanks is 15 pounds.

7.2.4 SPACECRAFT COMPONENTS

The guidance mechanisms, communication equipment, science payload, etc., for the flashlight reactor spacecraft, is the same as those specified for the externally fueled reactor spacecraft.

7.2.5 LAUNCH COMPONENTS

The launch adapter joining the flashlight reactor spacecraft to the booster is the same 250 pound unit designated for the externally fueled reactor spacecraft. The launch fairing for the 84 foot long flashlight reactor spacecraft weighs 4400 pounds of which 1030 pounds is the payload penalty.

8. WEIGHT REDUCTION AND POWERPLANT TRADEOFFS

8. WEIGHT REDUCTION AND POWERPLANT DESIGN TRADEOFFS

The power system reference design described in Section 1 is predicated on a number of judgments with regard to the technology and/or operating conditions of specific system components. The effects on power system characteristics of alternate technologies and operating conditions is discussed in this section. The factors of most interest, of course, are those which would improve the weight and/or output power characteristics of the overall system, such as:

a. Alternate radiator designs

   1. Beryllium-stainless steel conduction fin radiator

   2. Vapor chamber fin radiator

   3. Heat pipe radiator

b. Alternate reactor coolants

   1. Lithium

c. Power conditioning (PC) characteristics

   1. Maximum operating temperature

   2. Efficiency

   3. Temperature drop from PC module to PC radiator

d. Influence of reactor output voltage on system weight

Other factors which are of interest, but which may have an adverse effect on the power system characteristics include:

a. Alternate reactor coolant exit temperatures

b. The use of an unbonded (slip-fit) insulation sleeve in the TFE of the flashlight type reactor

The consequences of each of the alternatives listed above are estimated and discussed in the following paragraphs.

8.1 ALTERNATE RADIATOR DESIGNS

The radiator concept utilized for the reference system is a stainless steel conduction fin design with stainless steel/copper fins. The concept is state of the art with only modest development necessary to bring the design to flight readiness. However, there are alternate designs which offer potential weight savings over the stainless steel/copper radiator. The weight savings are achieved by using different materials, such as beryllium or graphite, or by using advanced heat conduction techniques, such as vapor chamber fins or heat pipes. Three of the more promising alternates are discussed below.

8.1.1 BERYLLIUM-STAINLESS STEEL RADIATORS

The weight and performance of a conduction fin radiator is primarily a function of certain physical properties of the radiator material. Ideally, the material should have a high thermal conductivity, low density, high modulus of elasticity, good strength, and corrosion resistance to the coolant. In the Cu/SS reference radiator, the stainless steel provides the structural strength, the high modulus of elasticity for meteoroid protection, and the corrosion resistance to the NaK coolant while the copper layer provides a high thermal conductance on the fin. But both stainless steel and copper are medium density materials, so the weight of Cu/SS radiators is relatively high for spacecraft applications which, in general, utilize light weight construction.

Beryllium is a low density material having the thermal and mechanical properties needed for high temperature radiator applications. Techniques for all types of metal forming and machining have been developed so that the quality and uniformity of fabricated beryllium products are now satisfactory for design purposes. Beryllium is readily attacked by NaK so another material is needed for the coolant channels. Of all the materials having the requisite liquid metal corrosion resistance, stainless steel best matches the beryllium properties. But techniques for brazing, braze welding, or diffusion bonding of the beryllium and stainless steel must still be developed before Be/SS radiators become a reality.

Figure 8-1 shows the cross section of a typical tube and fin assembly for a Be/SS radiator. The stainless steel is used only for coolant containment while the light weight beryllium forms the bulk of the radiator.

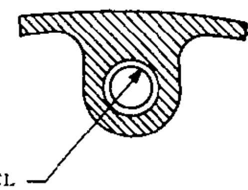

Figure 8-1. Cross Section of a Beryllium Stainless Steel Radiator

A comparison of beryllium-stainless steel and copper-stainless steel radiators for typical thermionic reactor conditions is presented in Table 8-1. A weight savings of 50 percent is realized for the Be/SS radiator along with a slightly smaller surface area, a lower coolant pressure drop, and a lower pumping power requirement. These factors combine to produce a reduction of 5 lb/kWe in powerplant specific weight.

TABLE 8-1. COMPARISON OF A BERYLLIUM/STAINLESS STEEL AND A COPPER/STAINLESS STEEL CONDUCTION FIN RADIATOR FOR EQUAL HEAT REJECTION

Characteristic	Beryllium-Stainless	Copper-Stainless
Heat rejected (kW)	1860	1860
Inlet temperature (°F)	1350	1350
Outlet temperature (°F)	1025	1025
System weight pump penalty (lb/kW)	500	500
Area (ft^2)	706	725
Effective radiator system weight (lb)	923	1825
Fin length (in.)	0.55	0.707
Fin thickness (in.)	0.031	0.030
Inside tube diameter (in.)	0.18	0.18
Tube liner thickness (in.)	0.015	0.015
Outside tube diameter (in.)	0.211	0.221
Total pressure drop ($lb/in.^2$)	1.42	2.18
Total radiator weight (lb)	842	1700
Meteoroid survival probability = 0.95		

8.1.2 VAPOR CHAMBER FIN RADIATOR

The use of vapor chamber fin (VCF) radiator is a possible method of obtaining a lighter, smaller, and more reliable heat rejection system than can be attained with a conduction fin radiator for high survival probabilities. Two principal reasons for considering the VCF radiator are the potential area reduction afforded by an isothermal fin and the possible weight savings due to a reduction in the meteoroid armor requirements. The use of vapor chamber fins enables a wider spacing between the primary fluid flow tubes and reduces the vulnerable area of this flow loop. Since a percentage of the vapor chambers can be allowed to fail, their armor requirements are usually satisfied by a minimum fabricable wall thickness.

A VCF radiator was designed for the same conditions used in the comparison of Be/SS and Cu/SS radiators. The example model utilized in the program is shown in Figure 8-2.

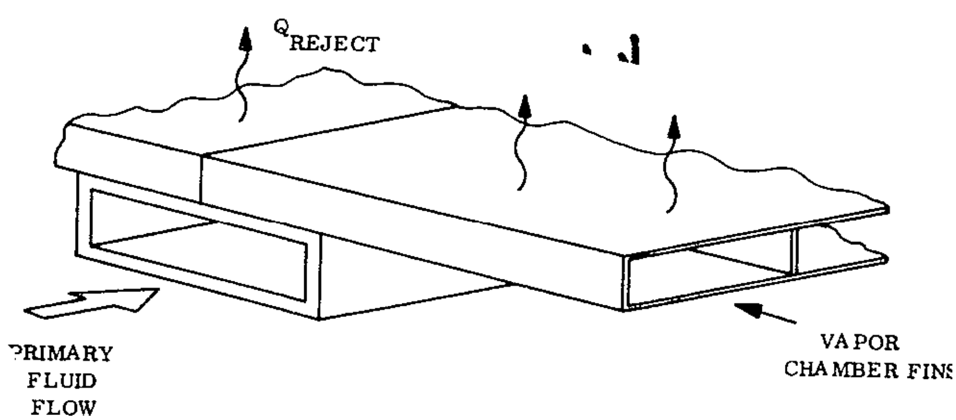

Figure 8-2. Vapor Chamber Fin Radiator Design Concept

Assuming all stainless steel construction with sodium vapor chambers, the VCP radiator weight is approximately equal to that of the Cu/SS example design. Primary characteristics of this design are shown in Table 8-2.

The apparent lack of a weight advantage of the VCF radiator when compared with the Cu/SS radiator is due to the relatively low meteoroid survival criterion of 0.95 being used. In order to show the conditions for which the VCF radiator would be advantageous, both VCF and Cu/SS radiators were designed for survival probabilities of 0.99 and 0.999. The results are presented in Figure 8-3.

TABLE 8-2. VAPOR CHAMBER FIN RADIATOR CHARACTERISTIC METEOROID SURVIVAL

Probability = 0.95

Characteristic	Value
Reference heat rejected (kW)	1860
Inlet temperature (°F)	1350
Outlet temperature (°F)	1025
System weight pump penalty (lb/kW)	500
Area (ft^2)	701
Effective radiator system weight (lb)	1822
Vapor chamber fin length (in.)	8.67
Inside chamber height (in.)	0.32
Inside chamber width (in.)	1.20
Chamber wall thickness (in.)	0.020
Inside primary duct height (in.)	0.25
Inside primary duct width (in.)	2.65
Primary duct wall thickness (in.)	0.020
Total fluid pressure drop ($lb/in.^2$)	0.251
Total radiator weight (lb)	1808

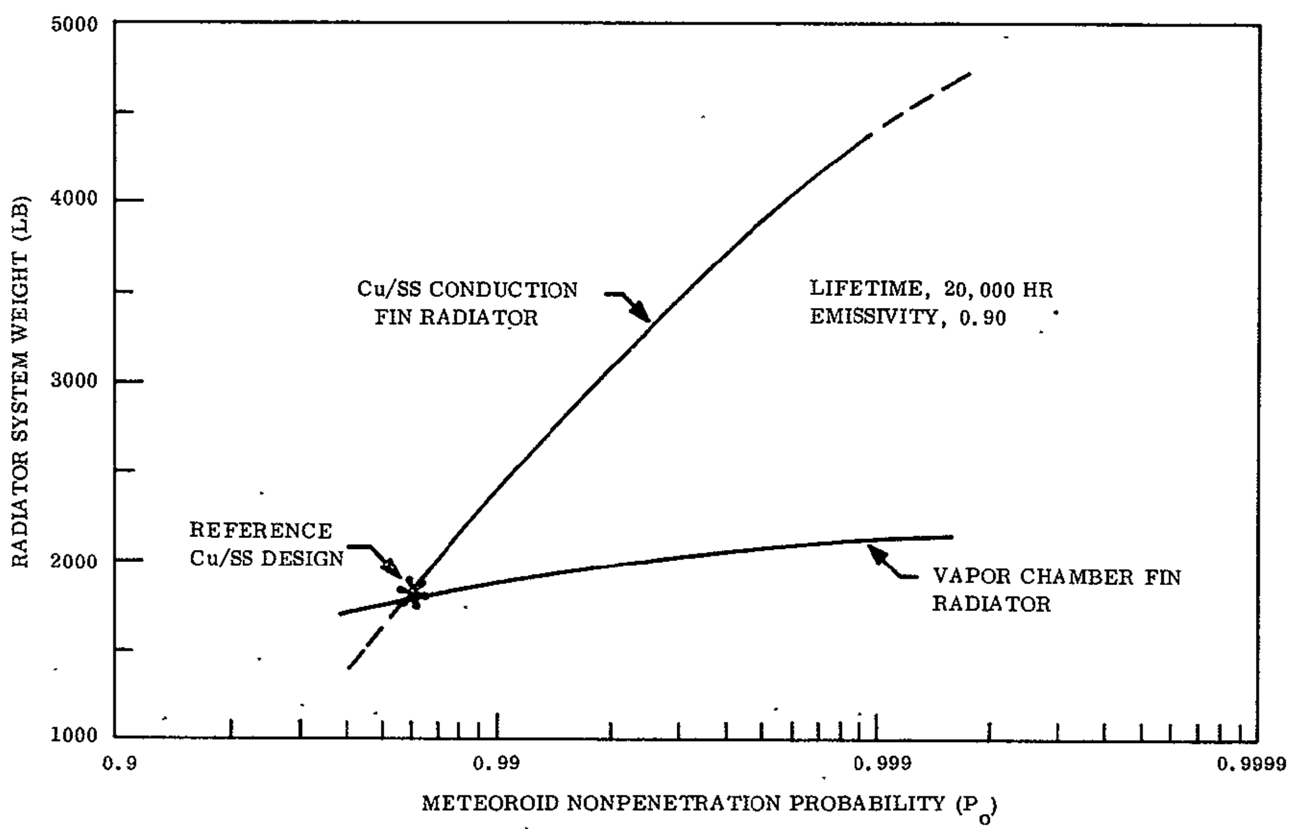

Figure 8-3. Effect of Meteoroid Non-Penetration Probability on Radiator Weight

As shown in the figure, the conduction fin radiator weight is extremely sensitive to variations in the meteoroid survival probability, P_o. The manner in which the design value of P_o affects radiator geometry is provided in Table 8-3. Increasing P_o results in longer, thicker fins and fewer, larger tubes with an overall decrease in vulnerable area.

While the conduction fin radiator weight increases by a factor of about 2.5 in going from a P_o of 0.95 to 0.999, the increase in the vapor chamber fin radiator weight is approximately 10 percent. The small effect of the meteoroid survival probability criterion on the VCF radiator weight is a direct result of the ability of the vapor chamber fin to allow a percentage of vapor chamber failures, without unacceptable damage to the radiator. The primary fluid loop in the VCF is well protected against meteoroids, since it is situated beneath the vapor chamber radiating surface.

8.1.3 HEAT PIPE - VAPOR CHAMBER FIN RADIATOR

The inclusion of VCF's in a radiator to eliminate the temperature drop occurring in the conduction fin suggests the replacement of the primary fluid loop with heat pipes as well. Such a design would have the advantages of eliminating the pump and associated hotel electric power load associated with this loop and could also result in a higher effective radiator temperature.

In such a design, energy would be transferred from the primary loop directly to an array of heat pipes situated in a heat exchanger. These heat pipes would form the main energy distribution system to the entire radiator.

Shorter heat pipes (vapor chambers), oriented perpendicular to the main heat pipes, would complete the heat rejection system to provide a high non-puncture probability. A conceptual design of this arrangement is shown in Figure 8-4. The main radiator has been placed near the shield in order to limit the primary heat pipe length. This necessitates moving the power conditioning radiator further away from the reactor, which results in greater losses in the low voltage electric cables.

An alternate configuration which avoids the problem of increased cable loss is shown in Figure 8-5. In this concept, the primary loop extends to the center of the main radiator. The primary heat pipes are limited in length to one-half of the main radiator length; therefore, the low temperature PC radiator can occupy the forward position. The potential disadvantage of this arrangement is that the primary fluid, which may be activated, passes close by the PC modules and comes much closer to the radiation sensitive payload.

Work performed for contract NAS 3-10615 was used to estimate the weight savings associated with the use of a heat pipe radiator for the thermionic powerplant conditions of interest. The total weight decrement including the elimination of the circulating pump and accumulators is approximately 800 pounds, or about 3 lb/kWe. As with the vapor chamber fin radiator, the relative weight savings are greater at the higher meteoroid survival probabilities because the heat pipe radiator weight increases only a few percent while the Cu/SS conduction fin radiator is more than doubling in weight.

TABLE 8-3. COPPER-STAINLESS CONDUCTION FIN RADIATOR WEIGHT FOR HIGHER RELIABILITIES

Parameter	Nonpuncture Probability	
	0.99	0.999
Reference heat rejected (kWt)	1860	1860
Inlet temperature (°F)	1350	1350
Outlet temperature (°F)	1025	1025
System weight pump penalty (lb/kW)	500	500
Area (ft²)	828	919
Effective radiator system weight (lb)	2373	4390
Fin length (in.)	1.11	1.61
Fin thickness (in.)	0.030	0.055
Inside tube diameter (in.)	0.185	0.203
Tube linear thickness (in.)	0.015	0.015
Outside tube diameter (in.)	0.281	0.397
Total pressure drop (lb/in.²)	4.73	6.51
Total radiator weight (lb)	2103	4018

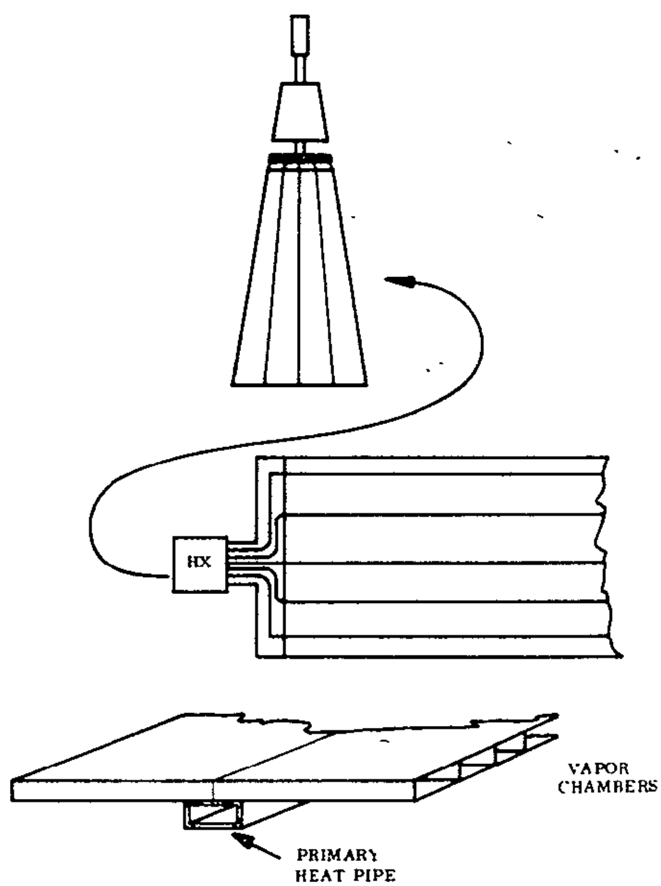

Figure 8-4. Conceptual Heat Pipe Radiator Configuration

8.2 ALTERNATE REACTOR COOLANT

Lithium has long been recognized as an excellent coolant for high temperature, high power density, compact nuclear reactors. Certain properties of lithium produce weight and specific weight advantages in the powerplant while other properties result in testing and operational disadvantages. A detailed investigation of all facets in the use of lithium in the reactor and main heat rejection subsystems is precluded by the scope of this study. However, a qualitative summary of the various advantages and disadvantages is presented, followed by estimates of the changes which accrue in the flashlight and externally fueled reactor powerplant specific weights when lithium is substituted for NaK.

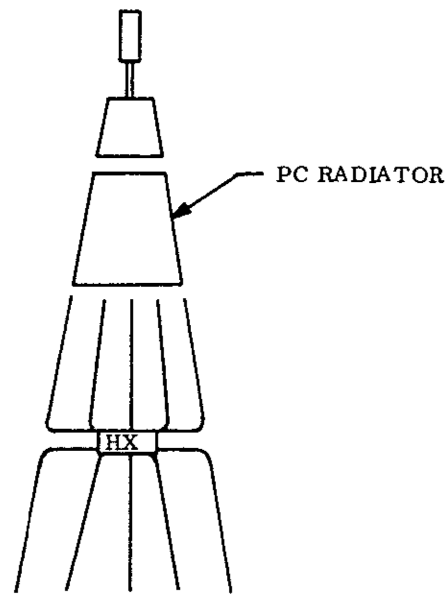

Figure 8-5. Alternate Heat Pipe Radiator Arrangement

The replacement of NaK with lithium in the reactor/main radiator loop(s) improves the characteristics of the powerplant in two ways:

a. The high specific heat of lithium (~ 1.0 compared to 0.2 for NaK) allows a corresponding reduction in coolant flow rate, or a reduction in coolant temperature rise, or some intermediate combination of the other two conditions.

b. Lithium, especially when enriched with Li^7, does not become highly radioactive like NaK.

A reduction in coolant flow rate in the lithium system produces one of the following conditions: a decrease in pumping power requirements if the component and piping sizes are maintained at the NaK loop dimensions, a decrease in component and piping sizes if the pumping power is maintained at the NaK loop values, or some intermediate combinations of the other two conditions. Changes in reactor size or coolant flow conditions are limited in scope if diode

dimensions, number and characteristics are to be maintained. Allowable changes in coolant flow area in the reactor are limited by a requirement to maintain a minimum gap between fuel elements that is not much smaller in physical dimension than the gap present in the reference design. Allowable changes in coolant flow rate may be limited on the low side to prevent laminar flow conditions in the reactor with corresponding flow maldistributions.

It is assumed that the maximum diode temperatures are the same in both NaK- and lithium-cooled thermionic reactors. Then, the possible reduction in coolant temperature rise in the lithium-cooled thermionic reactor is advantageous for two reasons: the average emitter temperature and the average collector temperature in the reactor may be increased. The higher average emitter temperature increases the voltage output - with corresponding smaller I^2R losses in the cable - and the gross electrical power output from the reactor. The higher average coolant temperature results in smaller, lighter heat rejection components, especially the radiator whose area requirements are inversely proportional to the fourth power of the average temperature.

The lower levels of coolant activation achieved with lithium will not reduce the primary shield thickness since the latter is set almost entirely by reactor considerations. However, for a reactor such as the current flashlight type, in which NaK becomes highly activated. lithium would allow the use of a single heat rejection loop configuration and the elimination of the heat exchanger and pumps present in the second loop. The resultant decrease in powerplant weight would be approximately 3 percent.

While the activation of lithium should not be a severe problem in the one-loop system, a hold-up tank can be included in the piping if the dose requirements are especially stringent. This approach would allow decay of Li^8, which has a half life of 0.85 seconds, in a region removed from radiation sensitive components. For example, a 10-second hold-up would reduce the dose level due to lithium activation by a factor of 3000 at a weight penalty of approximately 80 pounds, for minimum lithium flow rate conditions in a 300-kWe reactor.

The primary disadvantages of lithium stem from its corrosiveness to the more common containment materials and from its relatively high melting point. Unlike the other alkali metals, lithium is only marginally compatible with the stainless steels and the nickel base alloys at the temperature levels of interest to this study. Only the refractory metals have the required long term strength and corrosion resistance to lithium. Niobium alloys have been tested satisfactorily with lithium up to temperatures as high as 2000°F for 10,000 hours without evidence of corrosion. But niobium alloys oxidize readily in air at the operating temperature levels of interest, so system and component development of the powerplant would be extremely complicated by the inert atmosphere requirement for all tests at temperature.

Prior to startup of the thermionic reactor, all coolant loops must be heated or maintained at temperature levels above the melting point of the particular coolant. Lithium has a melting point of 354°F while the NaK eutectic utilized in the reference design has a melting point of only 12°F. Consequently, the preheat and/or the insulation requirements for the lithium cooled system would be considerably more difficult for an in-orbit startup of the system. The exact requirements for either system depend on the particular parking orbit chosen and the time interval between launch and power system startup.

First order estimates of the change in specific weight accompanying the substitution of lithium for NaK were made for both the flashlight and the externally fueled reactor powerplants. The estimates are predicated on a change in coolant flow rate only since data on the effect of a low coolant temperature rise in the flashlight reactor are not available. Component and piping sizes were held at the dimensions computed for the NaK reference systems but the containment material in the main heat rejection subsystems was assumed to be niobium alloy.

8.2.1 FLASHLIGHT REACTOR SYSTEM WITH LITHIUM

The reference flashlight reactor power system contains a dual primary heat rejection loop subsystem. The effect of lithium substitution for NaK was estimated first for the dual loop configuration and second for a single loop configuration. In the dual loop configuration, the changes which follow the lithium substitution are:

a. A coolant weight change since lithium has a lower density.

b. A change in coolant containment weight due to the substitution of niobium alloy for stainless steel.

c. A change in pumping power requirements.

The density of lithium at the average coolant temperature in the heat rejection loop is 29.2 lb/ft^3 while NaK density is 44.3 lb/ft^3. Consequently the total coolant weight in the heat rejection loops decreases about 34 percent.

The density of niobium alloy is 535 lb/ft^3 compared to 494 lb/ft^3 for stainless steel. Therefore, the weight of loop piping, heat exchanger, etc., increases by about 8 percent. The substitution of a niobium alloy radiator for the Cu/SS radiator will actually reduce the dry radiator weight by about 5.5 percent since the Cu/SS combination is heavier.

It can be shown that the ratio of lithium to NaK pumping power in a constant geometry system is given by:

$$\left[\frac{PP_{Li}}{PP_{NaK}}\right] = \left(\frac{\mu_{Li}}{\mu_{NaK}}\right)^{0.2} \left(\frac{C_{p\ Nak}}{C_{p\ Li}}\right)^{2.8} \left(\frac{\rho_{NaK}}{\rho_{Li}}\right)^{2.0}$$

where:

PP = pumping power requirements

μ = viscosity

C_p = specific heat

ρ = density

Substituting property data for a temperature of $1250^{\circ}F$, the above ratio is determined to be 0.032. Thus, the lithium pumping power is only a very small fraction of NaK pumping power. The 97 percent reduction in pumping power increases the net power to the thrusters by about 5 percent.

The resultant change in the specific weight of the two-loop flashlight reactor powerplant due to the weight and net power alterations given above is 6.4 lb/kWe.

The alteration of a two-loop, lithium cooled system to a single-loop, lithium system results in:

a. The elimination of the heat exchanger

b. An increase in radiator temperature due to the elimination of the temperature drop across the heat exchanger

c. Elimination of the pump power required to pump the coolant through both sides of the heat exchanger

The removal of the heat exchanger and the decrease in main radiator weight reduce the powerplant weight by 400 lb. The elimination of the heat exchangers adds a modest 0.05 kWe to net power value. The resultant decrease in powerplant specific weight for the change from two loops to a single loop is 1.6 lb/kWe. Therefore, the total specific weight advantage for a single-loop, lithium cooled flashlight reactor powerplant when compared to the two-loop, NaK cooled reference system is 8 lb/kWe.

8.2.2 EXTERNALLY FUELED REACTOR SYSTEM WITH LITHIUM

The reference externally fueled reactor powerplant is a high voltage, single heat rejection loop system. The substitution of lithium for NaK in the main heat rejection system provides the same advantages and disadvantages as in the flashlight reactor system, namely:

a. A coolant weight decrease

b. A slight increase in coolant containment weight

c. A significant decrease in pumping power

The percentage change in coolant weight, containment weight, and pumping power are the same as those quoted for the flashlight reactor. But the total resultant decrease in power-

plant specific weight is only 1.6 lb/kWe, a much smaller change than the 8 lb/kWe for the flashlight reactor system. The relatively small advantage for the externally fueled system is due to:

a. A much lower coolant inventory in the reference system. The externally fueled system does not have a heat exchanger and its main radiator feed lines are only one-third as long as the feed lines for the flashlight reactor system since its main radiator is located directly behind the shield. Consequently, the initial coolant inventory and the subsequent coolant savings are only one-half of the flashlight system.

b. A much lower pumping power in the reference system. The pumping power in the externally fueled reactor system is approximately one-fourth the pumping power in the flashlight reactor system. Consequently, the increase in system net power due to the substitution of lithium is also only one-fourth as great as the increase for the flashlight system.

c. The advantage of a single loop already exists for the reference system.

8.3 POWER CONDITIONING OPERATING CHARACTERISTICS

The reference flashlight and externally fueled reactor systems assume a power conditioning temperature of 200°F, a temperature drop of 25°F between the PC unit and the radiator fin root, and a PC efficiency of 86 to 88 percent for the flashlight system and approximately 92 percent for the high voltage externally fueled system. An improvement in any of these parameters can reduce the system weight substantially by decreasing the PC radiator size (and weight) which also tends to reduce voltage losses and cable weight.

The following paragraphs present the estimated improvement in powerplant specific weight accompanying the individual changes in power conditioning characteristics.

8.3.1 POWER CONDITIONING MAXIMUM TEMPERATURE

The effect of increasing the power conditioning temperature on the flashlight and externally fueled reactor system weights is shown in Figure 8-6. An increase of 100°F in the flashlight reactor PC temperature, to 300°F, yields a decrease of about 6 percent in specific weight and an increase of 1 percent in net power. A similar change in the externally fueled PC subsystem results in corresponding changes of 8.5 percent and approximately 0 percent, respectively.

8.3.2 POWER CONDITIONING EFFICIENCY

A significant change in the flashlight reactor system specific weight is possible with an increase in the power conditioning efficiency, as illustrated in Figure 8-7. For each percentage increase in the power conditioning efficiency, the system specific weight decreases by approximately 1 lb/kWe. The change in the efficiency from 88 to 93 percent also decreases the PC radiator area about 50 percent.

No substantial improvement in PC efficiency is probable for the high voltage externally fueled reactor PC subsystem which is assumed to be operating at approximately 92 percent in the reference design.

8.3.3 TEMPERATURE DIFFERENCE BETWEEN PC MODULE AND PC RADIATOR

The influence of temperature difference between PC module operating temperature and PC radiator temperature is shown on Figure 8-8 for the flashlight reactor system. Approximately 1 percent in powerplant specific weight is saved for a $10^{\circ}F$ decrease in temperature difference. Also, as shown, the effect is greater at the $200^{\circ}F$ nominal operating temperature for the PC modules than it would be if the modules were running at a higher temperature. In the externally fueled reactor system, the changes in specific weight would follow the same trends and be similar in absolute value.

8.4 ALTERNATE REACTOR COOLANT EXIT TEMPERATURES

A parameter having a significant influence on the characteristics of both the reactor and the overall power system is the reactor coolant exit temperature. In the reactor, conversion efficiency and the current-voltage characteristics of the output power are affected by the reactor coolant temperature, especially if the reactors are based on the same diode dimensional design. In the overall power system, the reactor coolant temperature influences the size and weight of the main radiator; the surface area, size, and weight of the low voltage electric cables; and the length, size, and pumping power required for the main radiator coolant feed lines.

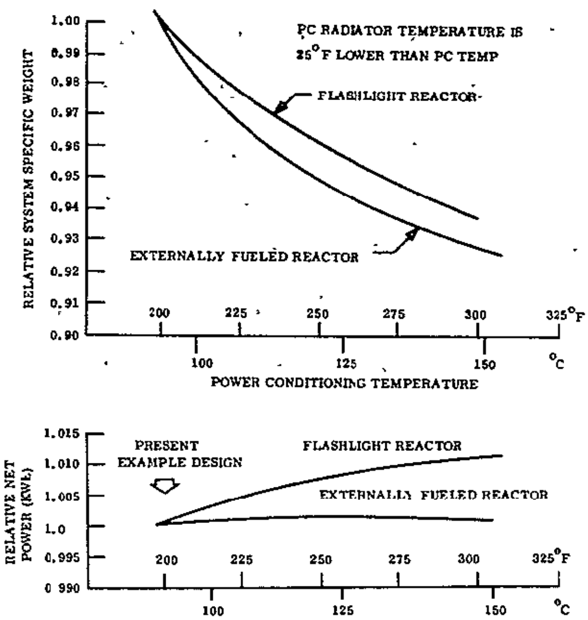

Figure 8-6. Influence of Power Conditioning Temperature

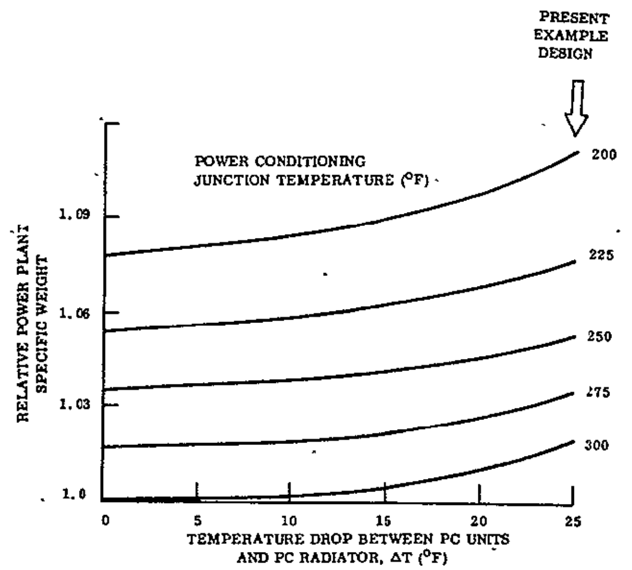

Figure 8-8. Relative Specific Weight as a Function of Temperature Rise for the Power Conditioning Unit and Power Conditioning Radiator

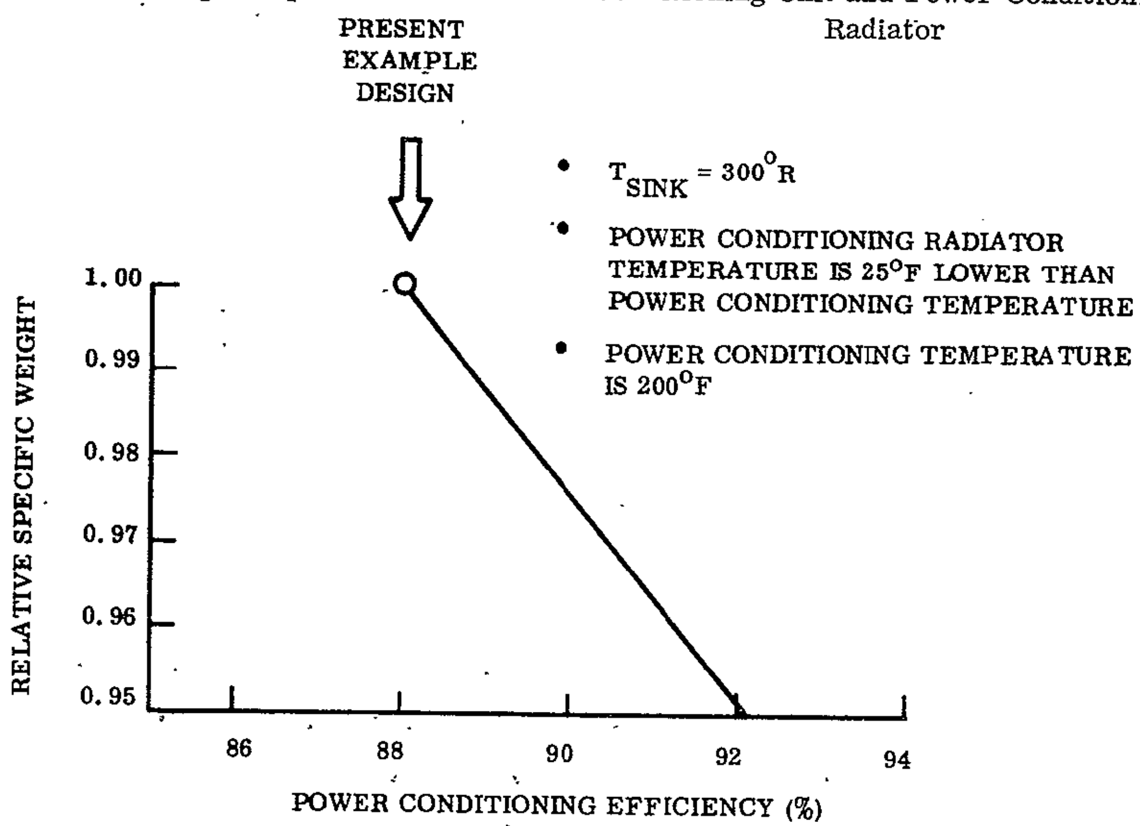

Figure 8-7. Effect of Power Conditioning Efficiency on System Specific Weight

In coolant temperature tradeoff studies performed to date, the maximum emitter temperature has been held constant, the maximum allowable of 2073°K for the externally fueled reactor and 1950°K for the flashlight reactor. Then, the change in coolant temperature results in variations of reactor output voltage and efficiency. In the flashlight reactor it is possible to maintain voltage, as coolant exit temperature is changed, by increasing the emitter temperature; however, the comparison would not be quite fair, since the base case voltage could be significantly increased if the emitter temperature were allowed to be higher. In actuality, the emitter temperature as well as details of the reactor and TFE geometry and other system parameters are subject to optimization in arriving at minimum plant weight or size for each coolant exit temperature, but fortunately these effects are secondary. The prime effect is the effect of collector temperature on reactor efficiency and voltage versus radiator size and weight.

8.4.1 EXTERNALLY FUELED REACTOR SYSTEM

The influence of reactor coolant exit temperature on the relative specific weight and output power is given in Figure 8-9 for the externally fueled reactor powerplant. The results show a minimum specific weight occurring at 1500°F exit temperature that is about 2 lb/kWe lower than the 1350°F reference case. A slight increase in reactor weight is more than offset by decreases in radiator weight and structure weight when the coolant temperature is raised from 1350° to 1500°F. The higher radiator temperature lowers its area and weight and the structure weight lessens because the lower radiator area results in a shorter vehicle length. In addition to the lower system weight, the net output power rises at the higher temperature. Shorter cable lengths generate lower electrical losses, and a higher coolant temperature rise in the reactor results in a lower required pumping power. The two effects combine to provide a slightly higher net power at the higher temperature.

8.4.2 FLASHLIGHT REACTOR SYSTEM

The estimated changes in power system specific weight and power output with variation in reactor coolant exit temperature are presented in Figure 8-10 for the flashlight reactor system. The changes are presented as ratios to the conditions existing in the reference system design, which has a coolant exit temperature of 1350°F. Increasing the coolant

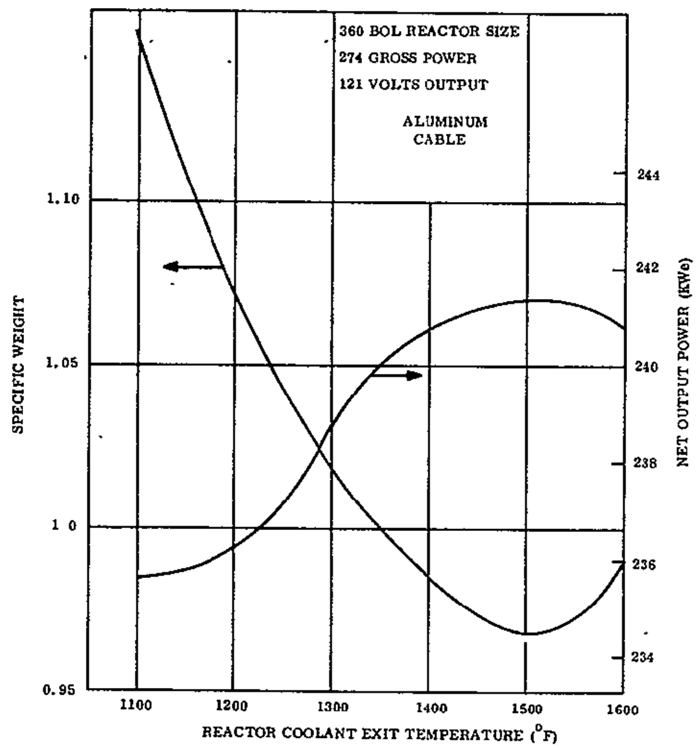

Figure 8-9. Externally Fueled Reactor - Effect of Reactor Outlet Coolant Temperature

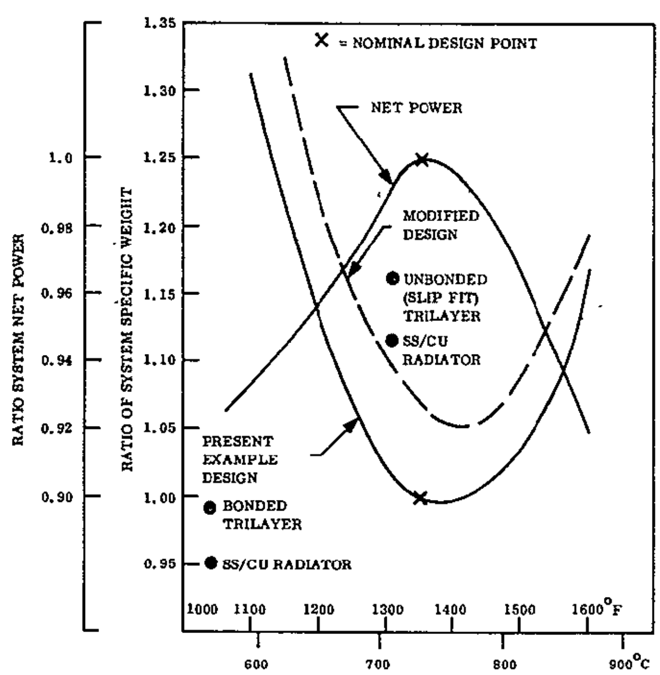

Figure 8-10. Effect of Coolant Outlet Temperature on Flashlight System Characteristics

exit temperature from the nominal design temperature to 1600°F decreases the net power by 8 percent and increases the power system specific weight by 17 percent. Decreasing the coolant temperature to 1100°F decreases the net power by about 7 percent, and increases the power system specific weight by 30 percent. In all cases, the coolant temperature rise in the reactor is optimized for the coolant exit temperature.

The lower reactor conversion efficiency at all temperatures other than the nominal design temperature produces higher heat rejection rates for a constant reactor electrical output. These higher heat rejection rates result in both higher pumping power, hence lower net system power, and bigger, heavier heat rejection radiators. At the low end of the coolant exit temperature range, the lower radiator temperatures increase the size and weight of the radiator, while at the other end of the coolant temperature range, the temperature effect on radiator size counteracts the effects of the lower reactor efficiency.

8.5 EFFECT OF UNBONDED INSULATION IN TFE

In the flashlight reactor design, use of a bonded trilayer produces a distinct performance improvement over the slip-fit designs, provided the nuclear penalties, which are not yet established, are not too severe. A coolant temperature increase of the order of 200°F can be realized at the same reactor efficiency by using a bonded trilayer, assuming the TFE design remains essentially the same in all other respects. Translating this into radiator weight gain for an unbonded design, it is possible to re-optimize the reactor coolant exit temperature as shown in Figure 8-10. Although the exact optimum temperature has shifted to a slightly higher temperature, there is little incentive to increase the exit temperature above the 1350°F level used in the fully bonded design. The system specific weight increase is about 6 percent or about 4 lb/kWe for the slip-fit TFE design.

9. MISSION OPERATIONS

9. MISSION OPERATIONS

An integral part of the design study of a thermionic reactor spacecraft is the operations analysis of pre-launch and post-launch activities and a nuclear safety evaluation of the reactor system. This section provides a plan for insuring that the integration of all engineering operations results in accomplishment of the mission. Also, a basis for conducting power system acceptance testing as well as a reactor safety analysis are presented.

9.1 OPERATIONS ANALYSIS

The purpose of this section is to describe the established mission profile including pre-launch flow plans and post-launch operations. Plans for the integration of the power system fabrication, test, installation, and operation with associated spacecraft, payload and launch facility functions have been developed so that these individual operations can be combined in an orderly and logical fashion to meet all mission requirements.

9.1.1 DEFINITION OF MAJOR EVENTS

Figure 9-1 presents in simplified form, the mission profile for a typical thermionic reactor powered spacecraft on a Jupiter Mission. The profile is broken into three segments: factory and test operations, launch site operations, and flight operations. The various spacecraft subsystems are first assembled at their respective sites and subjected to acceptance tests. Following these tests, the subsystems are joined together for operational checkout. The NASA Plumbrook Space Power Facility could accommodate the complete spacecraft assembly and could permit short term powered operation of flight units. Such testing must be incorporated in a schedule that permits the reactor fission products to decay sufficiently prior to their use during the relatively hazardous pre-launch countdown and launch ascent operations, and to permit safe shipment to the launch site. However, it is possible that Back Emission Testing (BET) could be used to eliminate nuclear testing.

Once at the ETR launch site, the thermionic spacecraft is installed on the already assembled Titan IIIC/7 launch vehicle. Launch vehicle and spacecraft tests are performed, spacecraft systems (e.g., coolant loops and propellant storage) are serviced, and the flight fairing is installed. The booster is then fueled, final checkout of all systems is completed, and the terminal phase of the countdown takes place.

The first three stages of the Titan IIIC/7 place the spacecraft in a low Earth orbit and the transtage is later fired to transfer the spacecraft to a 750 nautical mile orbit. At this point, communication with the spacecraft is established and the on-board systems are activated and checked out. Once acceptable performance levels have been verified and the orbit established, the reactor startup can be initiated. Following the achievement of criticality, the reactor is automatically controlled to a low power level (approximately 10 percent), and all auxiliary equipment is switched to reactor-produced power. The control system then brings the reactor to full power and the thrusters are activated, causing the spacecraft to spiral outward and ultimately assume a heliocentric orbit in its trajectory to Jupiter. During the transit time, the spacecraft is tracked and its thrust vector is controlled (by ground station commands) to maintain the desired trajectory. Commands transmitted to the spacecraft shut off the ion engines and reduce reactor power during mid-mission coast, and bring the reactor back up to full power so that retro-thrust can be applied during the latter phase of the transit.

At the appropriate point following encounter with the Jovian gravitational field and attainment of the required orbit, the science payload is deployed, the reactor power is reduced to a low level, and the ion engines are shut off. If a satellite lander capsule is included as part of the science payload, it would be separated from the spacecraft

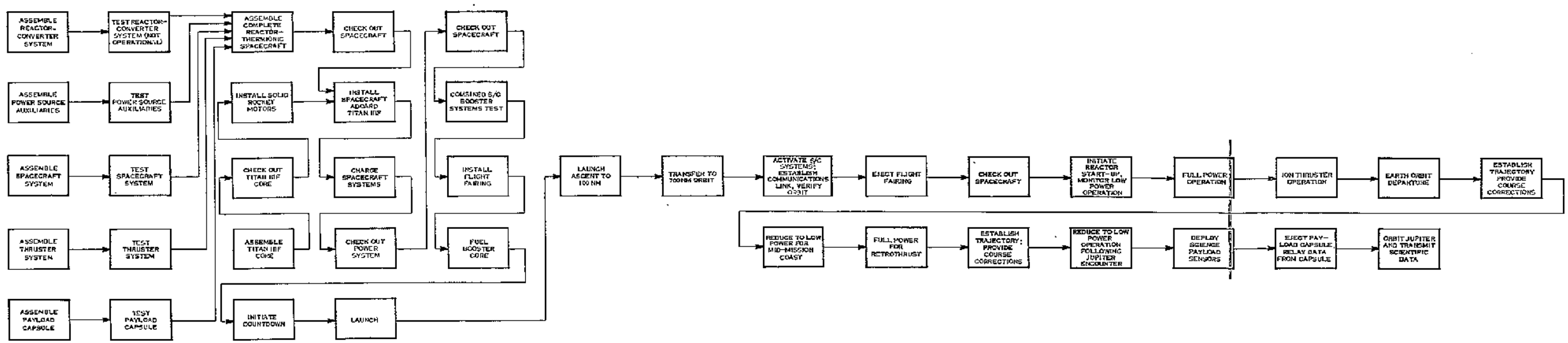

Figure 9-1. Typical Mission Reactor-Thermionic Spacecraft

FOLDOUT FRAME 1

FOLDOUT FRAME 2

when the appropriate relative orbital positions of the spacecraft and the Jupiter satellite (e.g., Callisto) is attained. The spacecraft then acts as a relay station for signals transmitted from the lander, while simultaneously transmitting data from on-board sensors as it continues to orbit the planet.

9.1.2 POWER PLANT STARTUP

Prior to reactor startup, power is required by several spacecraft systems, notably the reactor coolant loop and the reactor startup controls and instrumentation. The total power and energy requirements must be defined and a suitable auxiliary power system selected and characterized. Reactor startup cannot be initiated until the orbit altitude (750 nautical miles) prescribed by safety requirements has been attained and confirmed. Meanwhile, some of the following spacecraft functions that are dependent on electrical power must occur:

a. Circulation of reactor coolant

b. Heat addition to reactor coolant

c. Communications, including the transmitting of data and acceptance of commands by the spacecraft.

d. Instrumentation and control associated with reactor startup

e. Instrumentation required for monitoring and housekeeping

f. Operation of attitude control system.

Because of the potential hazards that occur during and prior to launch, the reactor probably will not be operated until the spacecraft has acquired a proper orbit. Reactor startup must therefore be remote and automatic when the spacecraft has reached the minimum safe orbit, and it has been determined that all systems are functioning properly, the reactor can be started and taken to full power operation. The spacecraft auxiliary power load can be taken over by the reactor power system and the short-lived auxiliary power sources can be deactivated, and if practical, jettisoned

to improve subsequent performance in the electric propulsion phase. Thrust operation will be initiated in accordance with ground commands. The procedures and equipment required to effect startup and the subsequent generation of power must be determined.

Procedures involved in reactor startup begin prior to launch; the step-by-step procedures required include the assembly of the reactor to the spacecraft and carry through to the production of thrust by the ion engines. Factors to be considered are the charging of the reactor coolant systems, the maintenance of sufficiently high coolant temperatures through launch ascent and during orbital flight prior to reactor startups, the detailed procedures of the startup and the controls and instrumentation required to effect it, the timing of flight fairing ejection, power requirements of the startup process, and the auxiliary equipment (both vehicle-mounted and ground support) required. In addition to detailed startup procedures, a startup system will thus be defined and consideration will be given to equipment redundancy and contingency planning in the event of component failures.

Specific areas of investigation include:

a. Means of preventing coolant freeze-up prior to startup of the reactor

b. Suitable means of shipping the thermionic spacecraft from the assembly and test site to the launch site

c. Mission contingency plans.

9.1.2.1 Primary Coolant During Startup

A critical aspect of spacecraft heat rejection system design is the behavior of the radiator under startup conditions. Fundamental to the problem of startup is the necessity for the radiator to respond to increasing power loads. This requirement demands that the radiator coolant be in a fluid condition when startup is initiated.

An investigation of radiator panel temperatures was conducted for a typical fin-tube geometry in a 750 naútical mile sun oriented, ecliptic orbit to estimate if the coolant in the thermionic spacecraft radiator system would freeze during the launch and orbit stabilization period. Since the launch time, trajectory and other specifics are unknown at this time, the object was to select a typical situation and assess the severity of the radiator startup problem. The assumptions used in this investigation include:

a. Conduction fin offset-tube geometry, stainless steel armor, stainless steel/copper fins (See Figure 9-2)

b. Incident heat flux varies with position as in a 750 nautical mile ecliptic orbit

c. NaK (78 wt % K) radiator coolant - freezing temperature of 12°F

d. Radiator emissivity and solar absorptivity of 0.9.

e. NaK is pumped into loop just prior to startup, therefore, its latent heat of fusion does not contribute to radiator heat capacity.

f. The radiator is cylindrical and is slowly rotating.

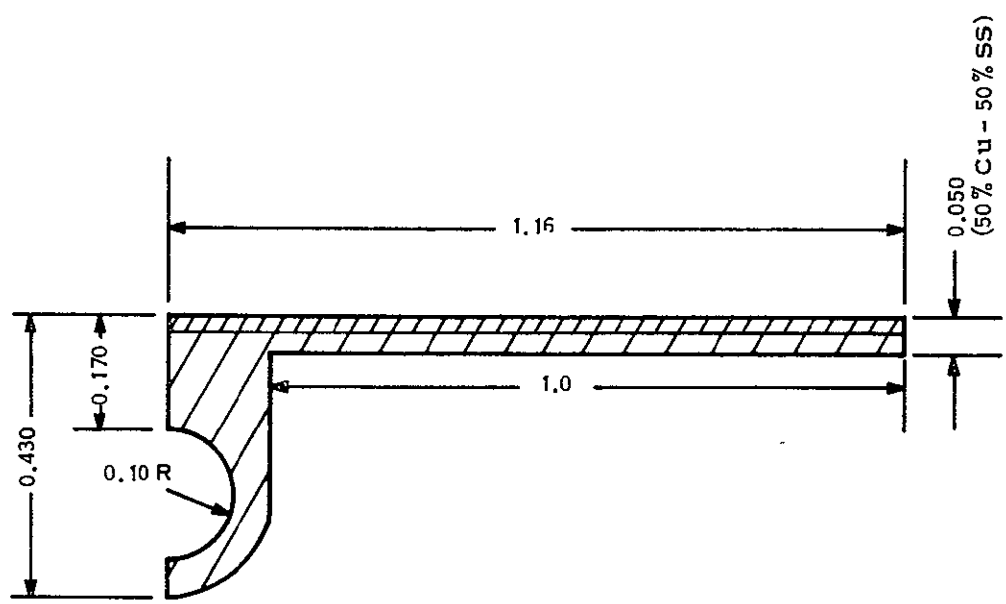

Figure 9-2. Model for Thermionic Spacecraft Radiator Startup Study

The results obtained from the analysis are shown in Figures 9-3 and 9-4. Examination of Figure 9-3 shows that for a wide range of radiator temperatures at the beginning of the sun portion of the orbit, the temperature of the radiator will reach approximately 120° to 140°F by the time it starts the shade portion. However, this situation results in a radiator temperature of -15°F by the time the vehicle again receives solar flux. In order for the radiator to remain above 12°F during the entire orbit, it must begin the swing behind the earth at about 310°F. The assumption that the NaK is not in the radiator is not required. Its effect is to reduce the temperatures during heatup by about 10°F, and increase the temperatures during cooldown by the same amount, relative to the data of Figures 9-3 and 9-4.

Whether or not the radiator will require pre-heating, insulation or an auxiliary power supply will depend on the startup power profile of the remainder of the system. A distinct possibility is present for system startup during the sun portion of the orbit, or during an orbit where a greater part of the time is spent in the solar flux.

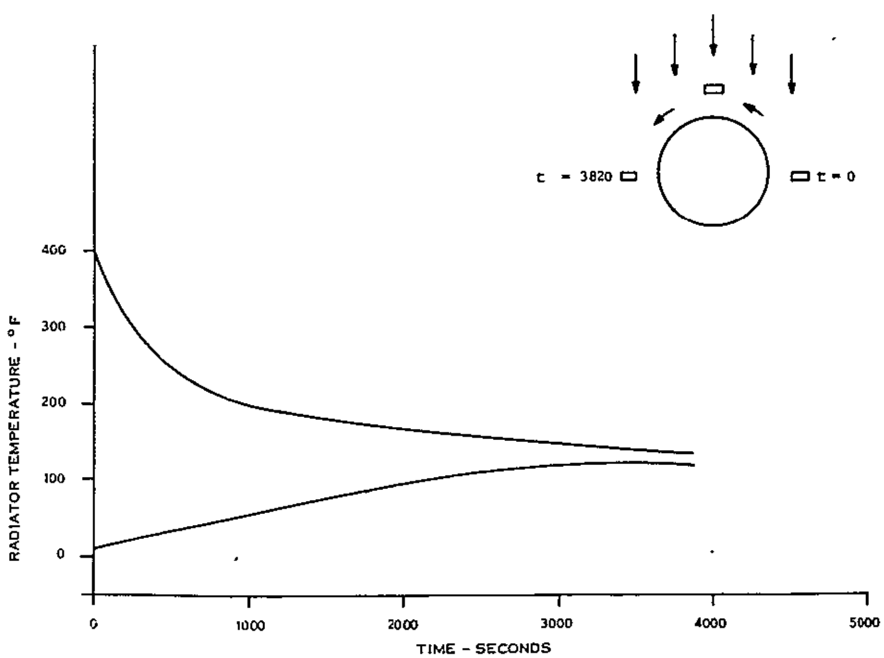

Figure 9-3. Radiator Temperature Transients

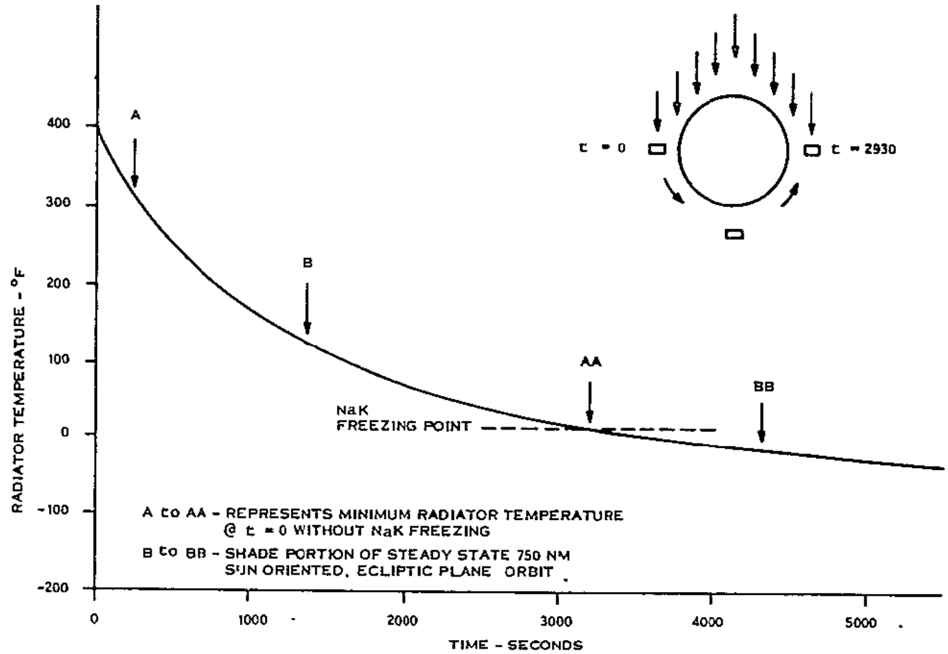

Figure 9-4. Radiator Temperature on Shade Side

Alternately, an orbit with a beta angle other than zero degrees may be selected. The radiator average temperature as a function of beta angle (angle between the sun ray and the orbit plane) for an isothermal cylindrical shape at an altitude of 750 nautical mile is shown on Figures 9-5 and 9-6. The cylinder considered was oriented with its roll axis parallel to the earth's surface, and perpendicular to the earth's surface. The ends of the cylinder were assumed to be blocked from seeing the external sink. The external conditions used were nominal, in terms of solar, albedo, earth and day of year.

The curves labeled orbit average in Figures 9-5 and 9-6 show the temperature for the whole body averaged over the orbit. Maximum instantaneous is the highest temperature during the orbit and minimum instantaneous is the lowest. For the case with the roll axis parallel to the earth's surface, the minimum temperature is -144°F

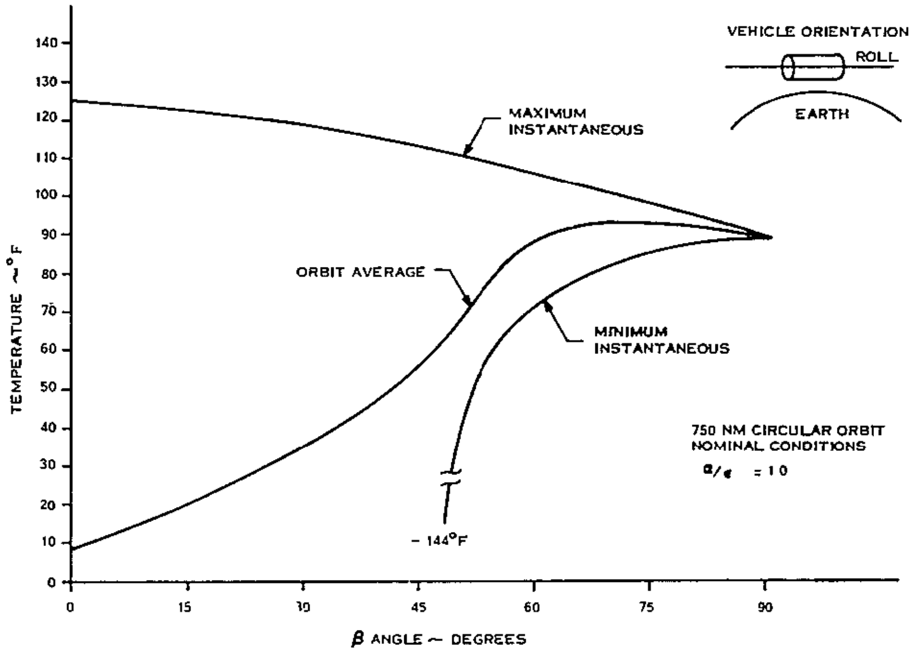

Figure 9-5. Radiator Average Temperature vs Beta Angle

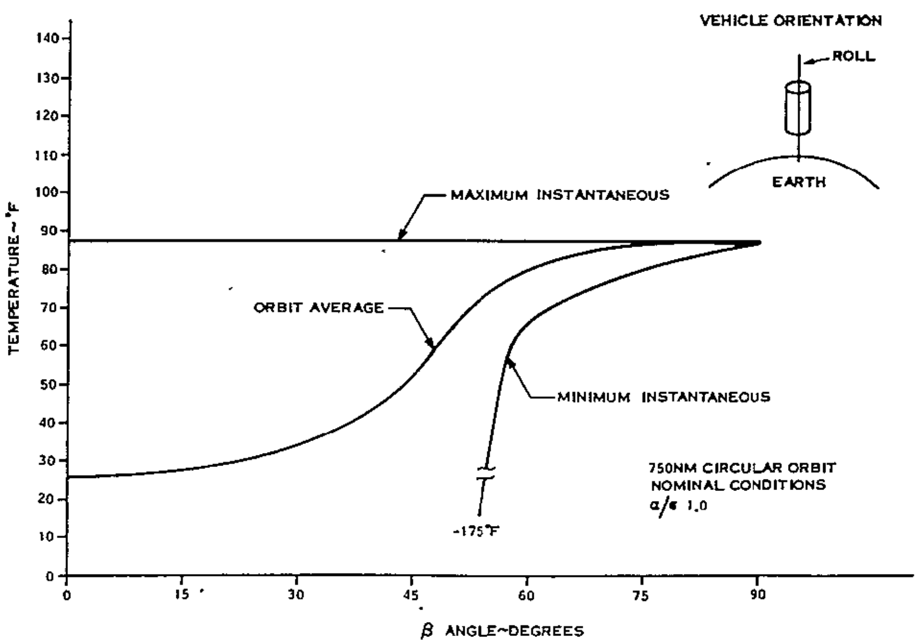

Figure 9-6. Radiator Average Temperature vs Beta Angle

and for the perpendicular case the minimum temperature is -175°F, when the beta angle is approximately less than 60°. The amount of shade time during which the sink is this minimum value can be found by referring to the curve in Figure 9-7 which gives the amount of shade time as a function of beta.

Consequently, proper selection of the earth departure orbit will eliminate the need for special startup heating or insulation for NaK-78 cooled power plants.

9.2 NUCLEAR SAFETY EVALUATION

9.2.1 PURPOSE AND SCOPE

An essential task in performing a design study for a thermionic reactor spacecraft is to provide a nuclear safety evaluation. The objective of this safety evaluation is to establish safety design criteria and performance objectives concurrent with reactor system development to assure a reactor configuration capable of safe mission operation. To obtain flight approval for the thermionic reactor powered spacecraft, the safety analysis must show that hazards and accident consequences

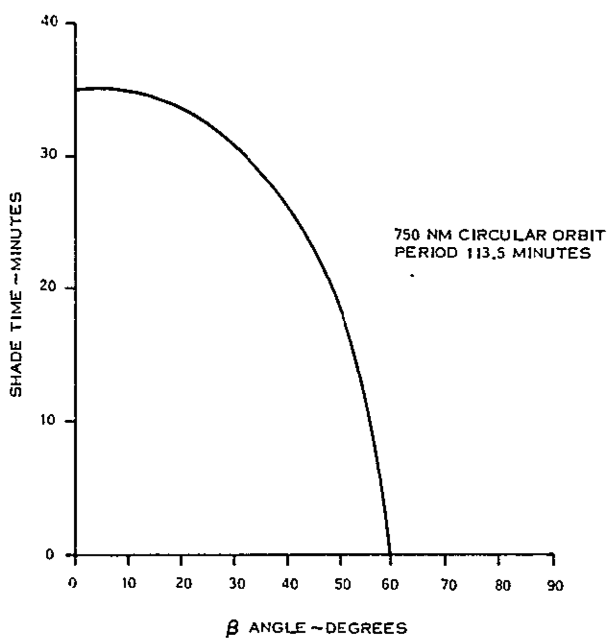

Figure 9-7. Shade Time vs Beta Angle

for each operational phase shall not involve an unacceptable risk to operational personnel and the general public.

The major areas which must be considered in reactor safety analysis are:

a. Identification of potential modes of failure in the ground handling, prelaunch, and flight phases of the mission which can affect the safety of the thermionic reactor system.

b. Assessment of factors affecting the probability of the identified failures.

c. Description of the environments to which the reactor system is subjected following the identified failures.

d. Evaluation of the effect of failure environment on the reactor system and determination of the probability for inadvertent criticality, as well as amount, condition, and location, of any fission product release.

e. Analysis of the potential radiological consequences of an inadvertent criticality or fission product release.

The safety analyses should be made concurrent with reactor system development. In some areas, analytical methods cannot predict failure modes or consequences with confidence. In these cases, a safety test program is conducted. Safety tests should verify the design capability to preclude radiological exposure to personnel and present data required to evaluate the potential hazard in the event that a failure occurs.

The safety of a thermionic reactor system for a Jupiter orbiter mission can be enhanced if the following approaches are employed:

a. Through restrictions on prelaunch integrated power, there should be a low fission product hazard from conceivable accidents during checkout or launch operations.

b. By delaying reactor startup until after the spacecraft has achieved a long lifetime earth orbit, i.e., about 500 years or greater, fission products will have decayed to non-hazardous levels by the time re-entry occurs.

c. By achieving a reactor design which would be incapable of (1) compaction into a critical configuration, or (2) inadvertent criticality induced through the control loop, the consequences of a pre-launch accident or post launch abort should not result in a radiological hazard to the general public.

This section provides the basis for the safety evaluation to be performed for a thermionic reactor spacecraft. Power system acceptance test requirements are presented, and a preliminary fault tree is developed to implement the application of probabilistic philosophy to the spacecraft reactor system. The information required for probabilistic definition of mission abort modes should be developed during the early phase of reactor system development. Possible hazardous operations and potential accidents are delineated for each operational phase of the mission.

9.2.2 ACCEPTANCE TESTING

Power system acceptance test requirements and mission safety requirements tend to be mutually exclusive. To reduce the possibility of undesirable radioactive fission product release in the event of a launch pad explosion or launch ascent abort, it is necessary to launch a reactor that has not been operated. This procedure is undesirable from the standpoint of acceptance testing since it affords no opportunity to verify the performance of the assembled thermionic reactor flight power plant prior to its commitment to the mission.

A number of approaches that satisfy both requirements to varying degrees are possible. Some possibilities are presented in Table 9-1, ranging from an approach that entails no direct testing of the reactor to one that involves a test of the completely assembled power system followed by a waiting period to permit fission product decay to acceptably low levels. The acceptability of each of the approaches and the selection of one as the best to employ obviously hinges on operational and design characteristics of the spacecraft power system support facility complex.

TABLE 9-1. REACTOR-THERMIONIC POWER SYSTEM PRELAUNCH TESTING

Test Approach	Comments
1. Build two reactor-thermionic diode power systems simultaneously. Test one system extensively by operation in appropriate facility; install other system in spacecraft for flight use without pre-launch operation.	Safety hazard is minimized but the assurance of acceptable performance from the thermionic reactor power system may also be minimized.
2. Simulate operational conditions within the reactor through the use of heaters or BET thereby obtaining test data that can be used directly or extrapolated to represent actual operating data.	Reactor and diode design must lend itself to use of heaters or BET. Simulated operation must reproduce actual conditions sufficiently well to produce meaningful test data. This approach might permit testing just prior to launch.
3. Fabricate reactor-thermionic diode system and operate the unit in an appropriate facility. After suitable time period for the decay of fission products within the reactor then proceed with assembly of reactor into the power system and spacecraft.	Safety hazard presented by remaining fission products must be analyzed. Length of time required to reduce fission products to acceptable level must be established. Post-operational assembly problems must be investigated.
4. Fabricate and assemble the entire power plant/spacecraft assembly and operate this entity in NASA Plumbrook facility. Provide suitable time period for decay of fission products within the reactor, then transport the spacecraft to the launch site for installation on the booster and subsequent launch.	Provides maximum assurance of ability to meet performance requirements, provided that fission product decay period is not too long and that suitable means of transportation from test facility to launch site are available. Safety hazard must be analyzed.

9.2.3 PRELIMINARY FAULT TREE ANALYSIS

The fault tree analytical technique permits the detailed evaluation of potential system incompatibilities or failure modes, and when used in conjunction with applicable failure consequence evaluation techniques, materially enhances the overall evaluation of the safety of a complex system.

The fault tree approach:

a. Assures an understanding of the overall system and its failure modes.

b. Identifies those areas where improved or specific data are required to predict system safety

c. Provides the overall failure mode probability information that permits determination of the degree of safety of a particular event in terms of its probability of occurrence.

d. Identifies those areas where program emphasis should be placed to enhance system safety.

The thermionic reactor spacecraft mission and events leading to mission completion are illustrated in Figure 9-8. The points of departure relating to mission failure or credible accidents, shown under each normal mission event define some of the failure modes in the preliminary fault tree shown in Figure 9-9. The symbols used in this fault tree are defined below:

The Rectangle identifies an event, usually a malfunction that results from the combination of fault through the logic gates.

The Diamond describes a fault that is considered basic in a given fault tree; however, the causes of the event have not been developed, whether because the event is an insufficient consequence, or the necessary information is unavailable.

The Circle describes a basic fault event that requires no further development. This category includes component failures whose frequency and mode of failure are derived through testing.

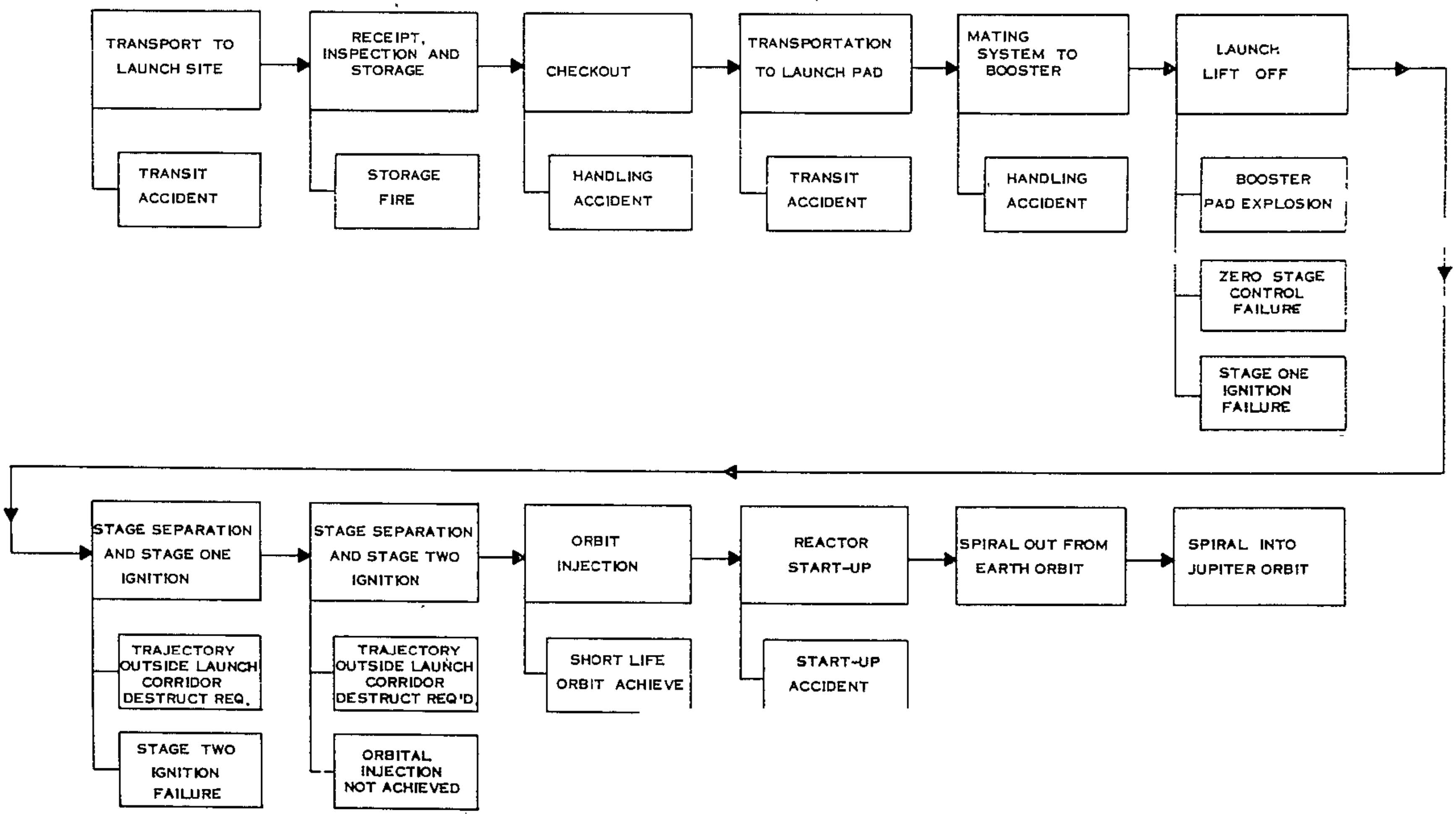

Figure 9-8. Proposal Mission Profile and Accident Groups for Unmanned Nuclear Powered Spacecraft for Planetary Exploration

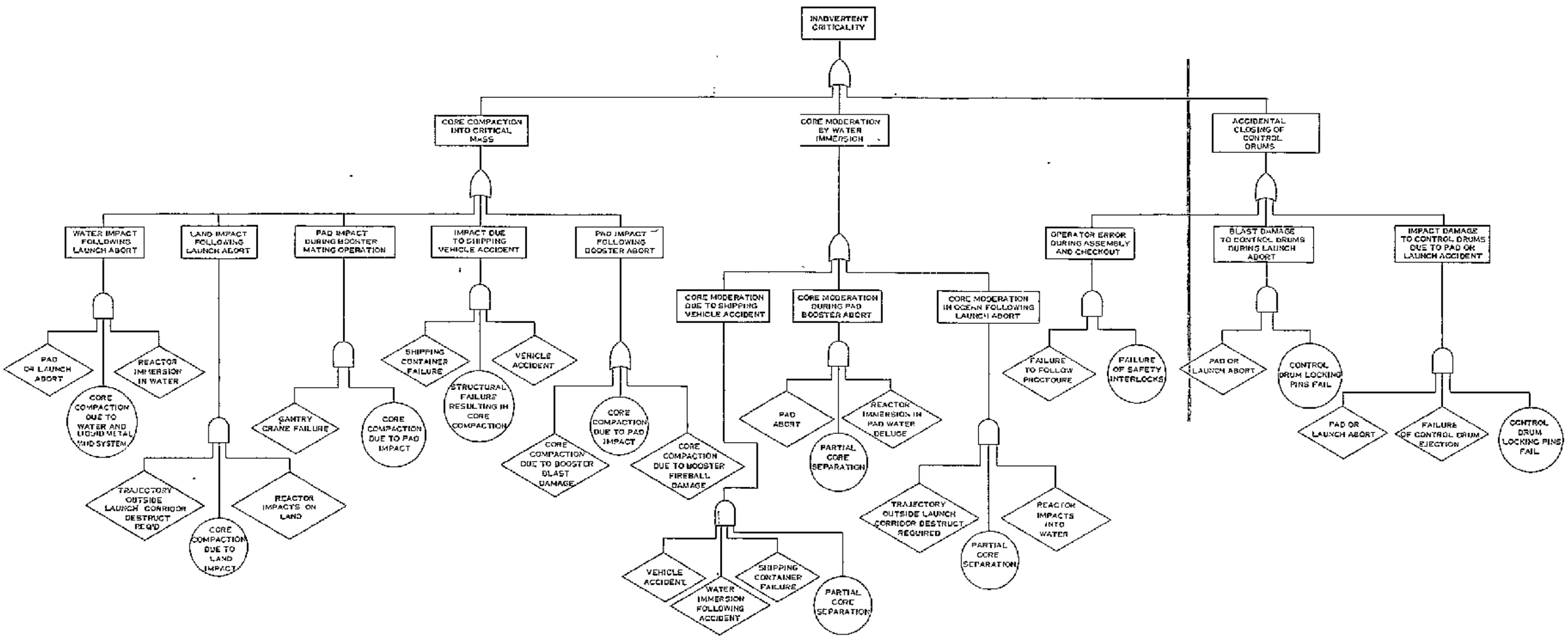

Figure 9-9. Preliminary Fault Tree - Inadvertant Criticality

FOLDOUT FRAME 1

FOLDOUT FRAME 2

The And Gate describes the logical operations whereby the coexistence of all input events are required to produce the output event.

The Or Gate defines the situation whereby the output event will exist if any or all of the input events are present.

Application of fault tree analysis to a thermionic reactor spacecraft system leads to the selection of the most undesired event as "Inadvertent Criticality." All the possible events that can lead up to this undesired event are defined and are used in the construction of the fault tree. Fault tree implementation requires that probability data be established for all identified events. The level of detail of this preliminary fault tree must be amplified to assure a complete safety evaluation. The identification of all contributing events and their probabilities will aid in identifying the direction and scope of the safety program, through the ability of the fault tree to focus on those areas where major effort may be required to assure that the safety requirements are achieved.

9.2.4 POSSIBLE HAZARDOUS OPERATIONS AND POTENTIAL NUCLEAR ACCIDENTS

To assess the nuclear safety problems associated with the utilization of a thermionic reactor system, a clear understanding of those types of accidents which may result in the release or generation of radioactive material is necessary. The mission phases where potential nuclear accidents may occur are:

a. Transport of reactor to launch site

b. Launch site handling and prelaunch checkout of reactor

c. Mating of reactor to launch vehicle

d. Launch

e. Earth orbit injection.

The potential nuclear accidents are identified, and the possible engineering safeguards which could preclude these accidents or reduce their consequences are discussed for the above listed mission phase.

9.2.4.1 Transportation of Power Plant to Launch Site

Transport accidents which can result in water immersion, core compaction, or control device movement may lead to a criticality. Engineering safeguards should substantially reduce the probability of an accidental criticality during transit to launch site. This includes removal of the reflector control drums in addition to enclosing the reactor in a shipping container designed to absorb the loads associated with a transportation accident and to prevent reactor water immersion.

9.2.4.2 Launch Site Handling and Prelaunch Checkout of Power Plant

Launch site handling may involve moving the power plant from the storage building to launch pad. Since the launch site is a controlled area, strict traffic control can be enforced during the transfer. Proper approved procedures and availability of instrumentation should reduce the probability of accidents occurring during reactor assembly, prelaunch reactor checkout, and launch site handling operations. Safety interlocks must be used after reactor assembly to prevent inadvertent closure of the control drums. The reactor startup command system must be fail safe and must not be accidently activated.

9.2.4.3 Mating of Spacecraft to Launch Vehicle

Upon completion of reactor assembly, the reactor will be mated to the launch vehicle. This mating operation is near the top of the launch vehicle. In the event that the reactor were to fall, core compaction and subsequent criticality may occur at pad impact. If the design objective of accomplishing a reactor design that is incapable of compaction into a critical configuration is met, this hazard would not exist. Aside from core compaction on pad impact, there is a remote possibility of a

criticality resulting from control drum closure. At this time in the prelaunch sequence and up to a few hours before launch, the reactor control drums should be secured in the open position by use of locking pins and/or nonreflecting void filler blocks (used on SNAP-10A).

9.2.4.4 Launch

The launch phase is perhaps the most hazardous phase from the standpoint of nuclear safety. An on-pad explosion and fireball, or an abort during boost, may subject the reactor system to the type of environment conducive to accidental criticality. Core compaction may occur from: blast or fragment damage; pad, land, or water impact; fireball damage; or liquid metal explosive reaction with pad deluge water or with the ocean where impact may occur. Core moderation may occur by reactor immersion in pad water deluge or falling into water. In fast thermionic reactors, hydrogen may have a limited worth and accidents involving water flooding of an unreflected assembly may not result in a criticality. Recent calculations indicate that for a near optimum hydrogen-to-uranium ratio, criticality will not be achieved as a result of water immersion.

Another consideration in minimizing the nuclear hazard from a launch abort is to specify both prelaunch reactor operation, if any, and post operation storage times so that the fission product inventory will be at an acceptably low level at the time of launch. Then, a launch accident which leads to the destruction of the reactor should not disperse fission products in hazardous concentrations. The ideal mission plan would be to start up the reactor for the first time after the spacecraft has been inserted into a long-lived orbit so that even those pre-launch and launch accidents which do not result in criticality will not result in any fission product release.

9.2.4.5 Orbital Injection

Should a mishap occur during the final booster orbital injection phase of the mission which would destroy the spacecraft or send it into an improper trajectory, it is conceivable that the reactor system may re-enter and impact on the surface of the earth. It may be required that the launch azimuth be selected such that failure of the launch vehicle up to orbital injection will result in reactor impact into the open ocean or on an unpopulated land area. Upon ocean impact, core compaction or partial core separation can lead to a nuclear excursion. Again, reactor design can reduce this risk. Some degree of ocean contamination would occur if the reactor went critical, but natural diffusion and ocean currents should reduce activity to acceptable levels within a short time and a small distance from the impact point.

If the spacecraft achieved a short-lived orbit, the reactor may burn up to some extent and impact onto a populated area. Since the reactor startup should not occur until the spacecraft has definitely achieved a long-lived orbit, fission products will not be released on re-entry burnup or land impact.

After the spacecraft is inserted into the desired longlived orbit, reactor operation will be initiated. A startup accident at this point should not have hazardous consequences, since the released fission products will have decayed to acceptable levels before they return to the earth's surface.

Once the reactor is removed from the earth's gravitational field into a heliocentric orbit, an earth re-entry hazard should not exist. Based on safety considerations, achieving solar orbit is by far the preferred method of reactor disposal.

10. CONCLUSIONS

10. CONCLUSIONS

1. High voltage electric power is the most effective means of reducing the propulsion system weight.

2. Heavy metal reflectors in the thermionic reactor raise the average neutron energy, minimizing coolant activation, and therefore permit the use of a single loop heat rejection system for the externally fueled system evaluated.

3. The conical (or conical - cylindrical) radiator, launched in the upright (apex: top) position on the launch vehicle requires 5 lb/kWe of support structure. The structual penalty for the inverted (apex: down) launch configuration is 1.5 to 2.0 times as great.

4. The triform, flat plate and cruciform tube and fin radiator geometries require at least twice the structural penalty requirement of the conical radiator.

5. Spacecraft of the type evolving in this study will have lowest natural frequencies of the order of one cycle per second. Redesign of the autopilot for the Titan IIIC/7 launch vehicle will be required to permit launching. This approach was utilized in the MOL program, and it is the best technique to maximize IMEO.

6. Special thermal insulation may not be required to permit power plant startup in the 750 nautical mile earth departure orbit when NaK-78 is employed as the primary radiator fluid.

7. The system power level must be maintained below 77 percent of full power during initial spiral out from earth orbit to limit electronic component temperatures to the maximum allowable of 200°F. Alternately, it may be acceptable to operate the electronics equipment above 200°F (about 230°F) for the 50 to 70 days required to spiral out to escape velocity from earth orbit.

8. A two-loop primary heat rejection system will be required for the as-designed flashlight reactor/spacecraft because beryllium oxide reflectors are used.

9. The weight penalty of a two-loop primary heat rejection system, compared to a one loop system, is approximately 550 pounds, or 2 lb/kWe.

10. A spacecraft flight fairing length of about 80 to 90 feet will be required on the Titan IIIC/7 launch vehicle (10-foot diameter). If this shroud is jettisoned in earth orbit, the payload weight penalty will be 100 percent of the shroud weight. If the flight fairing is jettisoned at Stage II burnout, the payload weight penalty will be only 24 percent of the shroud weight.

11. Comparison of aluminum, copper, and sodium metal in stainless steel tubing for low voltage cable material has resulted in the selection of copper-aluminum for both spacecraft concepts.

12. The flashlight reactor generates 318 kWe in order to supply 240 kWe to the ion engine. The propulsion system specific weight, α, is 71.1 pounds/kWe. The resultant spacecraft is approximately 84 feet long. The spacecraft powered by the externally fueled reactor requires a gross reactor output of 274 kWe to supply 240 kWe to the ion engines. The resultant spacecraft is approximately 62.7 feet long. Propulsion system specific weight, α, is 50.4 pounds/kWe. (Alpha values are based on power input to the power conditioning units.)

13. The failure of any one of the 108 main converter units in the flashlight reactor/spacecraft will result in a power loss of less than one percent.

14. All thermionic reactor main power conditioning units will require filtering of the reactor input power. For the flashlight reactor with 108 main converter units, the filter units represent a weight penalty of about 1.5 pounds/kWe. For the externally fueled reactor with 37 main power conditioning units, the filter units represent a weight penalty of 0.75 pounds/kWe.

15. The flashlight reactor electric system requires that all the thrust units operate in parallel from a single high voltage bus. Therefore, electric isolation will be provided for each engine to prevent the dumping of all thrust beam power into a single unit in the event of arcing. The weight penalty for the isolation system for all 37 units is about 1.0 pound/kWe.

16. The total defined payload and communications subsystems weight of these subsystems, including data handling components, is approximately 262 pounds. Since 2200 pounds has been allocated for the payload, an additional 1940 pounds is available for payload equipment.

17. The replacement of the copper-stainless tube and fin radiator with a beryllium stainless radiator would reduce the radiator weight by approximately 50 percent; or by 4.6 lb/kWe for the flashligh reactor and by 2.8 lb/kWe for the externally fueled reactor.

18. At the low 0.95 radiator survival probability, the vapor chamber or heat pipe radiator offers no weight advantage over the copper-stainless tube and fin radiator. At a 0.99 radiator survival probability, the vapor chamber fin offers approximately a 15 percent weight advantage, which increases to approximately 115 percent for a 0.999 radiator survival probability.

19. Replacement of the NaK-78 coolant with lithium in the flashlight reactor powerplant results in a weight reduction of 8 lb/kWe, whereas the same replacement in the externally fueled reactor powerplant results in a weight reduction of 2 lb/kWe.

20. An increase in the maximum allowable power conditioning temperature from 200°F to 300°F results in a reduction of about 4.3 lb/kWe for both the flashlight and externally fueled reactor based powerplants.

21. Each percent increase in power conditioning efficiency will result in a 1 lb/kWe decrease in specific weight for the flashlight reactor based powerplant. The corresponding incentive to increase the power conditioning efficiency for the externally fueled reactor powerplant is 0.5 lb/kWe.

22. Approximately 1 percent in powerplant specific weight results from each $10^{\circ}F$ decrease between the power conditioning diode junction and its radiator surface, based on an initial calculated value of $25^{\circ}F$.

23. The use of a slip-fit TFE assembly in the flashlight reactor, relative to the all bonded TFE assumed in this study, results in a powerplant weight penalty of about 6 percent, or about 4 lb/kWe.

24. The use of a dynamic power conditioning system for the low voltage flashlight reactor reduces the power conditioning weight from 10.7 lb/kWe to 7.2 lb/kWe and increases its efficiency from 88 to 93 percent. This efficiency increase, coupled with the ability of the dynamic system to operate at a temperature of at least $300^{\circ}F$ results in a 72 percent reduction in the PC radiator weight, about 2 lb/kWe.

11. RECOMMENDATIONS

11. RECOMMENDATIONS

1. The propulsion system weight penalty associated with low voltage thermionic reactors has been identified at about 20 lb/kWe. Evaluation of higher voltage reactors should be continued.

2. Techniques for raising the neutron energy spectrum of the flashlight reactor should be investigated to reduce coolant activation, permitting a single primary heat rejection loop.

3. Flashlight reactor designs permitting output voltages above 30 to 40 volts should be investigated for electric propulsion missions.

4. Increased weight savings of 2 lb/kWe can be realized if the externally fueled reactor coolant exit temperature is increased from 1350°F to 1500°F. The compatibility of the higher coolant exit temperatures with stainless steel technology and the need for refractory metal containment must be evaluated.

5. Copper-aluminum should be utilized for low voltage cable materials. The copper is required only at the higher temperature near the reactor location.

6. Shield analysis for the externally fueled reactor should be completed to the same degree accomplished for the flashlight reactor.

7. Investigation should be made of a power conditioning thermal radiation cooling concept in which each static power conditioning module is despersed uniformly over the individual radiator panel assigned to the module.

8. The feasibility of raising the power conditioning temperature from 200°F to 300°F should be investigated, including the effect on radiator weight and low voltage cable length.

9. The feasibility of decreasing the power conditioning unit to radiator ΔT, from 25°F to 15°F for example, by more efficient thermal contact should be determined.

10. During initial spiral out from earth orbit, the system power level must be maintained below 77 percent of full power in order to limit electronic component temperatures to the maximum allowable of 200°F. Alternately, it may be acceptable to operate the electronics equipment at about 230°F for this 50- to 70-day period. The effect of these alternates on power conditioning performance and mission time should be evaluated.

11. Filtering should be further investigated for all thermionic reactor main power conditioning units.

12. The conical (or conical-cylindrical) radiator configuration, integrated with the spacecraft and launched in the upright (apex: up) position on the launch vehicle should be employed to minimize spacecraft weight in earth orbit.

13. As soon as data are available for all powerplant components, a relative assessment should be completed.

14. Mission operations should be investigated in greater detail to permit improved definition of powerplant control system and startup operations.

15. Further evaluation of the dynamic power conditioning approach should be conducted.

16. Probability of mission completion should be assessed in terms of power system component reliability requirements.

17. The effect of U-233 fueled reactors on powerplant weight should be assessed.

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